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Municipal Wastewater Treatment Plant Sludge and Liquid Sidestreams

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MUNICIPAL WASTEWATER TREATMENT PLANT SLUDGE AND LIQUID SIDESTREAMS

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By ANTON A. KALINSKE

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PREFACE

This technical report represents a 1974 state-of-the-art in municipal wastewater treatment plant sludge and liquid sidestreams.

An important factor in determining the total cost of a wastewater treatment alternative is determining the component cost of any sidestream treatment and disposal system. Information from this report can be used as the technical input in determining the cost-effectiveness of a wastewater treatment alternative. The Cost-Effectiveness Analysis Guidelines (40 CFR 35, Appendix A, *Federal Register*, September 10, 1973) details the basic methodology for determining the most cost-effective waste treatment management system or the most cost-effective component part of any waste treatment management system proposed for a Federal construction grant.

Processing sludges by the methods described herein produces liquid sidestreams containing different types of pollutants. Such sidestreams are either treated separately or recycled to some upstream part of the treatment plant. The economic and technical factors involved in this recycling are delineated, since the associated costs of preventing sidestreams from degrading the desired final effluent quality are attributable to the sludge handling system.

Some treatment methods produce liquid sidestreams having high concentrations of soluble matter. In this case, processing the sidestreams before final disposal must be considered as part of the sludge process cost. Various advanced waste treatment processes can generate sidestreams not associated with sludge handling or processing.

In considering sludge disposal or utilization alternatives, it is especially important to consider environmental factors. The "Technical Bulletin on Municipal Sludge Management: Environmental Factors," in preparation at the time of this writing, should be available soon. Policy contained in the technical bulletin would have precedence over guidance contained in this technical report.

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1. INTRODUCTION

1.1 PURPOSE AND SCOPE

The purpose of this report is to provide background information on the handling and disposal of sludges and liquid sidestreams produced in municipal wastewater treatment works. Guidelines on these subjects are presented in separate publications. The intent of this report is to provide design engineers the information needed to arrive at environmentally sound and cost-effective methods of sludge handling and disposal.

The term "sludge," for the purpose of this study, includes all solid and semisolid wastes and suspensions of solids resulting from the operation of wastewater treatment facilities. The sludges produced can be entirely organic in nature, inorganic, or a combination of both, depending on the treatment processes employed in removing the suspended, colloidal, and dissolved pollutants from the wastewater.

The handling, treatment, and eventual disposal of the various sludges and process liquid sidestreams can create some difficult technical problems involving appreciable costs. The sidestreams often carry high concentrations of organic and inorganic matter suspended or in solution, since they are usually produced from methods involving the thickening and dewatering of sludges resulting from various physical, biological, and chemical treatment processes. Frequently, this matter has a high oxygen demand or consists of complex nonbiodegradable organic compounds. The treatment and disposal of wastewater treatment plant sludges and resultant sidestreams can account for 30 to 50 percent of the total treatment plant costs *(1)*.

The report *(1)* prepared by R.S. Burd in 1968 for the FWPCA on sludge handling and disposal contains much detailed information which generally is not repeated in this report.

It should be kept constantly in mind that sludges and sidestreams are an integral part of the entire wastewater treatment operation. They are not isolated processes or adjuncts to the main plant, either from a technical or economic standpoint. The handling, treatment, and disposal of such sludges and sidestreams must be evaluated as part of the entire treatment system. It is not possible to optimize the design of wastewater treatment works to ensure the required effluent quality, for the least capital investment and operating cost, without considering the sludge and sidestream handling and disposal methods as integral with the other processes.

1.2 GOALS OF STUDY

This study encompasses the treatment processes presently used in municipal wastewater treatment which are directly or indirectly involved in the production of sludges and liquid sidestreams. Processes which are as yet in the development or pilot plant stage are discussed on the basis of reported performance.

Certain sludge processing systems generate liquid sidestreams which can have an appreciable effect on the total plant performance and cost. Such processes are given particular attention, and the capital and operating costs are identified for several typical treatment plants (see appendix).

It is the goal of wastewater treatment works engineers, and the purpose of the plants they design, to dispose of pollutants with minimal effect on the total environment. Various pollutants are present in sidestreams, and their eventual safe disposal to the atmosphere, receiving water, or land can present some difficult technical and economical problems.

Since many pollutants which were not considered in the past are now being removed in sludges, and since the types and quantities of sludges will continue to increase in the future, we can be assured that the sludge handling and disposal problems will also become more complex and more costly to solve.

In the past, there was a tendency to minimize or ignore the "sludge problem." Various temporary or partial solutions, such as land dumping or lagooning, were adopted. However, such methods soon proved infeasible because of mounting concern over odor, groundwater contamination from leaching, and increased toxicity of industrial sludges. Also, population growth and development preclude the use of land for such purposes.

Currently, there are some wastewater treatment processes either developed or in the pilot plant stage which result in the production of minimal quantities of easily disposable sludge. These processes must be given special emphasis, since, as far as wastewater is concerned, one of the ultimate goals is the adoption of treatment methods that do not produce large qantities of sludges. Reduction in total sludge production—and generation of a type more suitable for eventual disposal—will reduce wastewater treatment costs significantly.

The primary goal of this report is to provide concise, up-to-date, objective, and comprehensive information on presently used sludge and liquid sidestream handling processes, including the final disposal steps.

2. DESCRIPTIONS OF TERMS USED IN REPORT

Though many of the terms in this report are commonly used by experienced engineers, it has been noted that in some publications the descriptions of certain processes are not consistent with general usage. A few important definitions are presented below. A more complete list of definitions can be found in the joint APHA, ASCE, AWWA, and WPCF *Glossary: Water and Wastewater Control Engineering*.

2.1 BRINES

A brine is any concentrated solution of inorganic salts; it need not necessarily be NaCl. Brines originate when it is necessary to remove soluble inorganic salts, which cannot be easily removed by chemical precipitation. The processes used include ion exchange and reverse osmosis, among others.

2.2 CENTRATES

This is the liquid extracted from a sludge in a centrifuge used either for thickening or dewatering. Its composition depends on the physical and/or chemical treatment of the sludge, the centrifugal force used in the unit, and the design of the centrifuge.

2.3 CONDITIONING OF SLUDGES

To release the liquid from sludges that are flocculant or of the hydroxide type, it usually is necessary to treat them with various chemicals, subject them to some drastic physical conditions such as heat or cold, or process them biologically. These processes, an extremely important part of overall sludge processing, are referred to as "conditioning," and may be necessary to accomplish the desired thickening or dewatering.

2.4 DEWATERING

Dewatering is the removal of additional liquid so that the thickened sludge attains properties

of a solid; that is, it can be shoveled, conveyed on a sloping belt, and handled by typical solids handling methods. Though there are some methods for final disposal of thickened sludges—and these will be discussed and evaluated in this report—most disposal methods require that the thickened sludge be further dewatered. Such dewatered sludge is usually in the form of a "cake," such as that produced by a centrifuge or vacuum filter. Frequently, dewatering can be accomplished with a high percentage of the solids retained in the cake; however, some sort of conditioning will usually be necessary.

2.5 FILTER BACKWASH WATERS

This is the water resulting from backwashing and removing the solids retained by a granular media filter. Various types of granular media filters, in which the media can be sand, coal, activated carbon, or mixtures, are used to physically remove most of the suspended solids, usually from settled effluents. Since these filters are periodically backwashed to remove the accumulated solids, the backwash water may contain suspended solids, usually well coagulated and compacted, and their concentration may vary from a few hundred to several thousand milligrams per liter.

2.6 FILTRATES

When sludges are dewatered on vacuum filters, filter presses, and other devices in which the liquid is separated from the solids by applying a differential force across a porous fabric or screen, the extracted liquid is referred to as "filtrate." Its characteristics depend on the sludge conditioning methods used, the chemicals applied, the character of the filtering media, and the type of sludge being processed.

2.7 FINAL DISPOSAL

Sludge, either thickened, dewatered, biologically or chemically altered, or reduced to an ash by incineration, must be returned to the environment. This final disposal must have a minimal detrimental effect, if any, on the environment. Final disposal will usually utilize the land or, in some cases, air or the ocean. Also, in some instances the end product resulting from any of several treatment steps, as will be described later in this report, can be reused by recycling back to some other treatment process where it will produce no adverse effects and can possibly have some economic value.

2.8 LIQUID SKIMMINGS

Much of the material that is skimmed from primary clarifier basins and also final clarifiers is liquid, such as oil or water with floating grease and other debris. It must be disposed of properly with the creation of the least amount of nuisance and odors. Typically, it is handled with the waste sludge from the primary clarifier.

2.9 MISCELLANEOUS WASH WATERS

Wash waters originate at various points in the treatment plant. Some of these originate only when equipment and working areas are washed down; others are more or less constant, such as the water used to wash organic matter from grit and scrubber water from incinerators for reducing particulate emissions below air pollution standards.

2.10 SAND BED DRAINAGE

This is the liquid that drains out of the sludge (usually digested) which is applied to sand beds for natural dewatering. Such beds, if properly designed, have a collecting underdrain system which carries the liquid to a point where it can be properly handled for disposal. It may have a high concentration of organic matter in solution and inorganic nitrogen and phosphorus compounds typical of digested sludge supernatants. If the sand beds do not have underdrains, the liquid that flows by gravity into the soil is called leachate.

2.11 SUPERNATANT

Supernatant is the liquid that is decanted from an anaerobic or aerobic digester. In domestic wastewater treatment works, such a liquid may have a high concentration of suspended and dissolved organic matter plus inorganics such as ammonium compounds, phosphates, heavy metals, bicarbonates of calcium and magnesium, as well as various types of pathogens.

2.12 THICKENER OVERFLOWS

Various sludges are thickened in gravity-type thickeners before processing. The overflow from such units is sometimes referred to as a "decant liquid" or "decantate."

2.13 THICKENING

A thickened sludge is one that is semisolid, though it has the gel-like characteristic of becoming fluid when shaken, stirred, or otherwise disturbed and of again becoming gel-like when allowed to stand. It can be pumped through pipes and handled essentially as a fluid.

Sludge solids are either originally suspended in wastewater or are generated by chemical precipitation or growth of biological organisms. Removal of such solids, at least as far as domestic wastewaters are concerned, is normally accomplished in relatively quiescent basins which allow the solids to settle out by gravity. This step is referred to as sedimentation or clarification. Simultaneously with clarification, some thickening of settled sludge frequently takes place. The solids that have settled thicken with time and/or by the aid of some slow-stirring mechanical devices such as pickets on scraper arms. The latter devices mechanically break up the agglomerated solid particles and release the liquid entrained or enmeshed in them. This is referred to as gravity thickening. Such thickening is often accomplished in a separate tank.

More thickening than can be attained by gravity settling is frequently required before further processing. This is especially true of the hydroxide type sludges generated by some chemical coagulants and of waste activated sludge. There are several methods which can be used to accomplish such thickening, and these will be discussed in detail in this report.

The technical and economic significance of sludge thickening is not always apparent or appreciated. Various treatment processes (plain settling, chemical treatment, or biological treatment) will produce sludge or solids whose weight is proportional to the weight of pollutants removed. However, the volume depends on the concentration of the solids in the liquid. For example, a sludge with 98 percent moisture has twice the volume of the same sludge thickened to 96 percent moisture, and thus would require twice the capacity in the next treatment processing units if some of the liquid is not removed.

2.14 WASH WATERS FROM SCREENS AND STRAINERS

A variety of screens can be used to remove either relatively large suspended solids or smaller solids on microstrainers. Such screens are usually self-cleaning or have a continuous stream of screened water for their cleaning. The wash water will contain a fairly high concentration of suspended solids which must be removed from the wash water, usually by return to the main treatment plant, before it is disposed.

3. DISCHARGE OF INDUSTRIAL WASTES TO MUNICIPAL WASTEWATER TREATMENT SYSTEMS

A detailed discussion of this subject is contained in EPA regulatory information on *Pretreatment of Industrial Wastes.* Industrial waste streams entering the domestic wastewater system must be identified. The potential effect of such streams may include: (1) impairment of biological treatment because of the effects of various heavy metals, toxic chlorinated hydrocarbons, industrial type detergents, etc.; (2) increased amounts of sludge produced, because of increased biological synthesis or a greater amount of inert material settling out in either the primary or secondary clarifiers; (3) production of much larger volumes and poorer qualities of liquid sidestreams, since various soluble organic compounds in industrial wastes, though biologically degradable, may produce sludges that do not dewater readily; and (4) excessive amounts of greases and oils (soluble and insoluble) entering a biological treatment process and having serious deleterious effects.

The extent to which sludge and sidestream processes at the municipal wastewater treatment plant will be affected by industrial wastes must be determined by bench-scale laboratory studies, extended pilot plant studies, or past experience.

Excessive concentrations of toxicants such as heavy metals, chlorinated hydrocarbons, and industrial type detergents can seriously interfere with the proper functioning of a biological treatment process, whether aerobic or anaerobic.

The sludge volume and type produced by either chemical or biological treatment of industrial wastewaters containing colloidal and soluble inorganic and organic compounds can be vastly different from those produced from domestic sewage. For example, the biologically synthesized solids resulting from removing a pound of BOD (biochemical oxygen demand) from some industrial organic matter can be different in character and quantity from the solids produced by biological removal of a pound of BOD from normal domestic wastewater.

The presence of certain types of inorganic solids can adversely affect the conditioning of sludge before dewatering. Any such solids and their possible effects upon the processes must be known before the sludge handling methods and processes are selected and designed into treatment plants.

It is possible for some industrial wastes to contain organic matter which is biodegradable, but the resulting sludge can have entirely different dewatering characteristics. It is therefore important that treatment studies be undertaken where necessary before the plant design is finalized, or before acceptance of the industrial wastewater for treatment, not only to establish the treatability of the industrial waste when mixed in the proper proportions with domestic wastewater but also to determine the amount and characteristics of the combined sludge to be treated.

Oils and grease decrease the density of floc and its settling rate in the final clarifiers, thus decreasing the density of the settled sludge. Oils and grease also inhibit the activity of the organisms by coating their surfaces and reducing oxygen transfer. Experience has shown that, in general, for any biological wastewater treatment process the total oil and grease concentration should not exceed on the average about 50 mg/l, so as not to impede the settling of the solids and their thickening*(2)*. If tests and experience indicate rapid biodegradability, higher concentrations are permissible.

Information on pretreatment of industrial wastewaters is contained in the EPA guidelines developed pursuant to Section 304 of the Federal Water Pollution Control Act Amendments of 1972.

4. TYPES AND CHARACTERISTICS OF SLUDGES AND LIQUID SIDESTREAMS PRODUCED

4.1 GENERAL DISCUSSION

This report is concerned with sludges that result from processes employed in municipal wastewater treatment works in the treatment of domestic wastewater mixed with those types of industrial wastewaters that are handled in such plants. Many of these methods produce solids by physical, chemical, or biological means.

The quantity and quality of sludges produced are based on the wastewater characteristics and the combination of treatment processes used. It is apparent that data gaps exist, as far as sludge production is concerned, in understanding the effects of combined treatment processes such as chemical coagulation with the activated sludge process. Because of the costs involved in disposing the solids generated by wastewater treatment methods, a unified design approach must be used. In the analysis of sludges and of bench or pilot simulation of treatment methods, some quantitative figures are of value regarding the amount of solids generated by various treatment processes and their water content, since dewatering of the solids is an important and expensive part of solids handling.

Table 1 shows ranges of amounts of sludges produced by various treatment processes*(3)*.

It is significant to note that settled activated sludge contains about three to seven times more water than settled trickling filter sludge. For processes used in sequence, the volumes shown in Table 1 may be additive, depending on when and if the sludges are mixed and decanted. The range of values, as far as weights of solids and volumes of sludge produced, can be quite broad and is dependent on the strength of the wastewater, the BOD loading used in the biological processes, the type of chemical used for coagulation, and the temperature and pH of the wastewater. Because of the wide variation in sludges, care and good judgment must be exercised in using typical values or extrapolating results from one plant to another.

Since most liquid sidestreams are generated when sludges are treated and processed for disposal, their characteristics and quantities will be discussed in this report in conjunction with the various methods used to thicken, stabilize, and dewater the sludges produced by various treatments.

TABLE 1. CHARACTERISTICS OF SLUDGES PRODUCED BY VARIOUS TREATMENT PROCESSES

Treatment Processes	Pounds Dry Solids per Million Gallons	Gallons Sludge per Million Gallons Wastewater Treated	Percentage Water in Sludges
Primary settling	900-1,200	2,500-3,500	93-95
Activated sludge	600-900	15,000-20,000	98-99
Trickling filters (low loading)	400-500	400-700	93-95
Trickling filters (high loading)	600-900	1,200-1,500	96-98
Chemical precipitation of raw wastewater	3,000-4,500	4,000-6,000	90-93

4.2 PRIMARY TREATMENT PLANTS

The term "primary" describes a plant utilizing screening facilities, grit removal, and settling. The settling basin is used to remove readily settleable solids and floatable materials such as oils, greases, and other debris.

Primary treatment will remove about 25 to 35 percent of the BOD_5 of the raw domestic wastewater and about 60 to 65 percent of the suspended solids. In a primary plant, the following sludges and liquids are removed from the main wastewater stream:

1. Grit and similar solids
2. Grit wash water
3. Solids removed by screening or changed in size by communition equipment
4. Skimmings, usually pumpable
5. Settled sludge—usually 5 to 8 percent solids. However, a high-rate (short term) primary plant may produce a sludge of only 2 to 3 percent solids. The solids loading is increased if there is a substantial amount of ground garbage.
6. Waste sludge from secondary clarifiers.

The sludge from a primary settling basin has been called "fresh" sludge. Of course, sludge is rarely "fresh" since anaerobic conditions rapidly develop, especially in warm climates, and the sludge can be quite odorous. In fact, many primary basins are the source of the distinctive and unpleasant odors the public associates with wastewater treatment plants. Many new, and even some older, activated sludge plants have been built omitting the primary basin and thus incidently eliminating the associated odor problems. Trickling filter plants using rock media require primary sedimentation to avoid clogging of the media with large solids and stringy material which get past any screening arrangements.

Manually operated or automatic screens remove solids which, in some plants, may be ground up and discharged back into the flow. In larger plants such solids are hauled away and disposed of with municipal garbage and refuse. Comminutors installed in a channel are essentially disintegrators which reduce the solids that are larger than can pass through, say, a 3/4-in. bar screen opening. However, comminutors can "string out" rags and allow them to pass through.

Skimmings, which may contain an appreciable amount of grease and oil, are conveyed into a trough or box located near the periphery of a circular clarifier or the end of a rectangular clarifier. Skimmings can be pumped to a sludge dewatering process such as a vacuum filter or a digester. They usually do not require any further thickening prior to biological digestion or a dewatering unit. At small plants such skimmings are disposed of to a landfill site or to an incinerator.

Preaeration is sometimes provided ahead of a primary clarifier to supply some oxygen to wastewater which may be septic or on the verge of anaerobiosis. Preaeration tends to delay septicity in the primary clarifier, produces some flocculation (and thus assists in removing some of the slower settling solids), and assists in floating greases and oils to the surface of the clarifier. It also scrubs the oil and grease from the other settleable solids. Such treatment is of considerable effectiveness in reducing odors that emanate from primary basins.

Pressurized-air flotation units have been used in a few cases to handle overflows from combined stormwater and sanitary sewerage systems. A 24-mgd (million gallons per day) plant of this type is in operation in San Francisco. The process starts functioning automatically to handle the excess flow resulting from storm flows*(4)*. Pilot plant tests were run on primary treatment using partial flow pressurization and flotation for the raw wastewater of Rio de Janeiro; as a result, a 240-mgd plant is being designed*(5)*. The principal advantage of using flotation for such primary treatment is the substantial reduction in required land area and the reduction in capital costs. Operating costs tend to be higher than those for gravity settling and skimming*(6)*. The sludges produced are handled in the the same manner as those from primary settling basins.

Hydraulically cleaned screens have been tested in the field for use on stormwater flows and also for primary treatment of domestic wastewater. Some tests have shown them capable of removing most of the floatables and settleable solids and 35 percent of the suspended solids*(7)*. A full-scale installation is being constructed to handle raw wastewater in Contra Costa County, California*(8)*. The stream containing the solids is about 5 to 10 percent of the main flow. Although much more concentrated than raw wastewater, the liquid stream containing the suspended solids would not usually be considered a sludge, and it would definitely require further thickening or dewatering.

4.3 SECONDARY PLANTS

Typically, a secondary treatment plant incorporates those processes used in a primary plant and follows them with a biological process. The objectives of this type of plant are to remove most of the carbonaceous oxygen demand matter, both soluble and colloidal; to remove most of the suspended solids; and possibly to oxidize other oxygen-consuming pollutants such as ammonia. The two common secondary treatment methods are trickling filters and the activated sludge process. However, there are numerous modifications of these general types, and the specific design used depends on plant size, climatic conditions, the desired effluent quality, and cost.

Bacterial activity results in cell synthesis which is a significant portion of the total sludge produced by the process. A portion of the organic matter or any pollutant will be converted by aerobic biological activity into a solid, and the excess solids, not required for carrying on the treatment process, must eventually be disposed of in some manner. The amount of solids produced, as a fraction of the pollutants removed from the wastewater on a weight basis, will vary considerably depending on the type of biological process used. The volume of waste sludge produced will amount to about 1/2 to 2 percent of the volume of the raw wastewater being treated.

In biological treatment, it should be kept in mind that the various aerobic organisms remove pollutants by two basic processes. One of these is the result of organism growth, which is referred to as synthesis. Most of the organisms, called *heterotrophs*, obtain the carbon and other elements for their cell growth from the organic substances present in the pollutional matter. During their growth process, these organisms oxidize a portion of the carbon and hydrogen present in the organic matter to CO_2 and water. Organic matter is usually absorbed through the cell wall and then synthesized and oxidized by complex chemical processes controlled by enzymes that the bacteria produce. If the organic matter is in the form of a colloidal or suspended particle, the cell attaches to the particle and an exoenzyme solubilizes the solid matter so it can be absorbed through the cell wall. The cell requires energy to carry on its life cycle and growth, and obtains this energy by oxidizing a portion of the organic matter into CO_2, water, and other oxidation products. In contrast, other bacteria, known as *autotrophs*, can use only inorganic carbon (from CO_2 or bicarbonates). The organisms responsible for oxidizing ammonia into nitrites and nitrates are autotrophs, for example.

4.3.1 Trickling Filters and Other Fixed Growth Systems

The conventional trickling filter uses rock media on which the biological organisms are attached. The biological growths adsorb and remove pollutants as the wastewater flows down over the surfaces. The biologic activity in the attached growths is quite complex, and various theories have been developed to describe the biological kinetics. It appears that some anaerobic decomposition may occur in the film at the rock surface, since the diffusion of oxygen through the film is largely molecular and thus quite slow, even though the film outer surface may have a relatively high concentration of dissolved oxygen. This anaerobic action, and resultant reduction of volatiles in the growths, probably accounts for the increased density of the sludge from trickling filters.

The excess solids synthesized slough off the rock surfaces; however, this tends to occur somewhat erratically depending on the factors such as pollutant loading, temperature, and hydraulic loading. These solids settle out in the final clarifier that follows the biological treatment process, and the excess matter that must eventually be removed from the treatment system. The biological and physical characteristics of the solids from trickling filters depend to a large degree on the BOD loading. Standard rate units generate about 0.25 lb of solids per pound of BOD removed, while high-rate filters will produce 0.50 to 0.85 lb. The solids from trickling filters will normally thicken in the clarifier to 2 to 3 percent by weight with the denser solids resulting from low-loaded filters*(9)*.

It should be emphasized that trickling filters do not in any sense remove suspended solids by physical filtration, and the term "filter" is basically a misnomer. In recent years plastic media, usually polyvinyl chloride, have been used. The media consist of plastic sheets which provide more surface area per unit media volume and considerably more open volume than rock, thus aiding air movement. Because of their light weight, such media can be used in units 20 ft or more in height, thus reducing required area *(10) (11)*. The excess solids produced from such units are generally comparable to those from units with rock media. For economic reasons, such media have been used primarily for high BOD loadings per unit volume, and in such cases the solids production increases to between 0.5 and 1.0 lb per pound of BOD removed.

A fixed media type unit that has been extensively field tested for both domestic and industrial wastewaters is the rotating biological contactor *(12) (13)*. The unit was originally developed in Germany, and there are presently over 700 installations in Europe, most under 1 mgd in size. There are at least 12 plants installed or under construction (1973) in the U.S. The units consist of a series of disks mounted on a horizontal shaft. The disks (made of light plastic material) are closely spaced and provide a relatively large area for biological growths. The wastewater flows through a tank, which may be compartmentalized, in a direction perpendicular to the rotating disks which are submerged in the slowly moving wastewater to about three-eighths of their diameter. The alternate contacting of the disks with the wastewater and the atmosphere provides oxygen for biological removal of biodegradable pollutants from the wastewater. Removals of 85 to 90 percent BOD and suspended solids from domestic wastewater have been reported. The solids slough off the disks and are carried with the flow to a final clarifier. The quantity and physical characteristics of the solids are comparable to those from trickling filters.

Another type of fixed media biological treatment unit that has been tested, but on a pilot plant scale, is the aerated packed tower*(14)*. Wastewater flows upward together with dispersed air bubbles, and biological growth occurs on the media surfaces. Units in which the tower is flooded and anaerobic conditions develop, with growth of the denitrifiers on the media, have been studied for denitrification of wastewater*(15)*. A similar unit was recently tested on a pilot plant scale for nitrification of ammonia in wastewater. The tests included the use of air and pure oxygen*(16)*.

Fixed media biological reactor units generally produce waste solids that tend to be denser and faster settling than those from the activated sludge process. This, of course, is desirable for the collection, handling, and eventual disposal of such waste solids*(17)*.

4.3.2 Activated Sludge Plants Using Air

This treatment process uses a suspension of aerobic microorganisms to remove soluble and colloidal organic matter. The organisms can vary widely in concentration, type, and degree of agglomeration, depending on various physical features designed into the treatment plant, the pollutant loading, type of pollutants, and degree of pollutant removal. There are many modifications of the activated sludge process. From the basic definition, this process includes plants consisting of aerated lagoons—high-rate aerobic processes which have concentrations of microbial suspensions on the order of 2,000 to 5,000 mg/l in aerated basins and which are designed primarily for removal of the carbonaceous BOD (5-day)—and low-rate processes designed to oxidize ammonia to nitrates. The high-rate processes are characterized by a high rate of excess solids production, since the removal of carbonaceous BOD at a high rate involves high synthesis. Nitrification is at the other extreme, since the organisms involved have a relatively low reproduction rate and therefore the excess solids produced per pound of ammonia (nitrogenous BOD) oxidized are very small.

The process for removing carbonaceous pollutants can be operated at a relatively low loading rate (pounds of BOD_5 per pound of MLVSS per day), thus reducing the amount of excess synthesized solids and the percentage of volatile matter in such solids. This loading rate would be about 0.05 to 0.15. Such a process is frequently referred to as extended aeration, and approaches aerobic digestion. The excess solids produced will be about 0.05 to 0.25 lb per pound of BOD removed, while in a high-rate activated sludge process the solids production may be between 0.75 to 1.0 lb per pound of BOD removed.

The activated sludge process, called "extended aeration" or "total oxidation," is practiced when the BOD loading per pound of mixed liquor volatile suspended solids (MLVSS) in the aeration basin is below about 0.15 lb/day. For years it was believed by many engineers that such long periods of aeration would result in oxidation of all the organic matter and that there would be only inorganic residues remaining. It was discovered that in all such plants there was some insoluble organic matter which, if not biodegradable, was only very slowly degradable. From a practical standpoint, some of the solids would have to be removed; otherwise, they would go out with the plant effluent.

It is not the intent of this report to describe all the numerous ways that the activated sludge process can be carried out, since the literature on this subject is quite extensive. The principal point that should be emphasized is that variations in the design parameters of the process can have a profound effect on the character and amount of excess solids that are produced. Solids from these systems are the most difficult to thicken and dewater of any that are produced in wastewater treatment plants, and their disposal can account for a large portion of the total cost. Therefore, methods to make them thicken faster and dewater more readily, with the creation of a minimum amount of other problems, should be carefully evaluated by the design engineer. Some extra costs in the actual treatment process may produce a more than comparable reduction of costs in the waste solids handling and disposal.

As was indicated in Section 4.3.1, there appears to be a basic difference in the physical and biological character of the solids produced when the growths occur on fixed media and when they are in an agitated suspension. Many problems that seem to be commonly experienced with the activated sludge process are unknown in trickling filter plants. One example is the so-called "bulking" of the sludge, which often occurs under conditions in which the cause-effect relationships are not very clear.

4.3.3 Activated Sludge Plants Using Pure Oxygen

The use of pure oxygen instead of air for supplying the required oxygen to the microorganisms in the activated sludge process was studied over 20 years ago. However, only recently has it become possible to use the process practically, because of the various technical improvements and significant lowering of costs for on-site oxygen production systems. However, there are some technical limitations and the *total* costs of an oxygen system, as compared to a modern aeration system, are not necessarily always in favor of the oxygen system *(18)*.

The solids in the aeration basin can be carried at a higher concentration than with air systems. The concentration of the sludge drawoff from the final clarifier in the oxygen system is about 1.0 to 2.5 percent; in the normal operation of an activated sludge system using air the solids are usually not more than about 1 to 1.5 percent by weight*(19)(20)*. The settled solids can be thickened further using a flotation thickener, which can produce 4 to 5 percent solids.

4.4 CHEMICAL ADDITION TO PRIMARY PLANTS

Chemical treatment of raw wastewater was practiced fairly extensively in the 1920's and 1930's. However, as the activated sludge process came more and more into use, it became apparent that it could produce a higher quality effluent at lower operating cost. A good review of chemical treatment is given by Culp*(21)*. Chemical treatment is now coming back into use for the following reasons: (1) it can reduce BOD loads on an existing secondary plant, (2) it can precipitate phosphorus, (3) it can be combined with a subsequent physical treatment process (activated carbon) to obtain an effluent comparable to biological treatment with reduced space requirements and reduced sludge handling costs, and (4) it can take advantage of organic types of coagulants (polymers). Polymers accomplish coagulation with much less increase in total solids in comparison with inorganic chemicals.

Inorganic coagulants such as alum, iron salts, lime, or organic coagulants can be used to capture the finely divided suspended solids and a portion of the colloids in a primary clarifier. These coagulants are mixed with the raw wastewater which is then flocculated and settled. With such treatment, suspended solids removals from domestic wastewater of 85 to 90 percent can be obtained and BOD removals of 55 to 70 percent are possible. The sludges resulting from treatment with inorganic chemicals are frequently dewatered and disposed of in landfills (when stabilized using lime treatment at pH of at least 11.5) or incinerated with garbage and refuse. If organic coagulants are used, the sludge volume is considerably less and such sludges can be digested before dewatering. Sludges produced with alum or iron coagulant treatment can also be digested. No solubilization of the precipitated aluminum phosphate occurs, though some may occur when ferric phosphate is reduced to the ferrous form in an anaerobic digester*(22,23,24,25)*. Presently, lime treatment of raw wastewater is frequently used, with the addition of a coagulant aid such as one of the polymers if needed. The pH is raised to about 9.5 or 11.5, depending on what degree of phosphorus removal is desired and the calcium and magnesium content in the wastewater. The precipitated calcium carbonate and, if the pH is above 10.5, some magnesium hydroxide accomplish coagulation of the suspended and colloidal matter. The settled sludge is quite dense—around 10 percent by weight at the lower pH—and is usually easily dewatered without further conditioning. It must be recognized that addition of coagulants can substantially increase the weight of solids to be treated.

The amount and density of the solids produced by various chemical treatments of raw domestic wastewater are shown in Table 2. These values are based on the solids discharged from primary clarifiers*(26)*.

TABLE 2. PRIMARY CLARIFIER SOLIDS RESULTING FROM CHEMICAL TREATMENT OF RAW WASTEWATER

Treatment	Pounds per Million Gallons	Percentage Solids
Lime		
pH>11.5	3,000–12,000	5.0
pH<11.5	2,000–10,000	11.0
Iron coagulant	9,000–20,000	1.5–2.0
Aluminum coagulant*	5,000–10,000	0.5–1.0

*Polymer may be desirable.

The amount of sludge produced will depend on the alkalinity of the wastewater and the degree of phosphorus removal desired.

Biological digestion of sludge which has been treated with lime for phosphorus precipitation might not be effective. Some experiences reported recently in Ontario, Canada, indicate that high pH sludge must be added to the digester with some control to prevent digester upset*(27)*. It was stated that raw wastewater was treated with lime to a pH of 10.5. By keeping the sludge in the bottom of the clarifier for some 1.5 days, the pH dropped to 9.5 and then, by proper pumping of the sludge to the digester, normal operation of the digester was maintained at a pH of about 7.0 to 7.4. The calcium phosphates solubilized to only a minor degree; there were only 6 to 8 mg/1 of phosphorus in the supernatant, which was less than that in the raw wastewater. The digested sludge had a solids concentration of 10 to 11 percent.

A 30-mgd plant that will employ lime treatment of raw wastewater in a primary clarifier, followed by an activated sludge-nitrification stage and then denitrification, is being designed for Contra Costa County in California*(28)*. The sludge from the primary basin will be incinerated and calcined after centrifuging. These processes will be discussed later in this report.

4.5 CHEMICAL ADDITION TO SECONDARY PLANTS

The requirement for reduction of phosphorus in wastewaters to a low level has brought about the use of chemical coagulation as a separate or integrated process in wastewater treatment. Either alum or an iron salt, such as ferrous sulfate, will precipitate orthophosphate as an insoluble aluminum or iron phosphate at normal pH values. Of course, use of these coagulants, depending on the alkalinity of the wastewater, results in an appreciable precipitation of either aluminum or iron hydroxide. Studies have indicated that alum, aluminate, or iron salt can be added in an activated sludge aeration basin or in a separate mixing basin or compartment between the aeration basin and the final clarifier. Since the phosphates precipitate at pH values in the range of 6 to 8 when an aluminum or iron salt is added, no adverse effect on the biological activity has been noted*(29)*. The hydroxides produced tend to coagulate the finer particles of the activated sludge and to improve the clarification and settleability. Although the quantity of solids increases, the total volume of sludge is not greatly increased, since these settled solids produce a denser sludge. Also, tests have shown that there is no adverse effect on either anaerobic or aerobic digestion of the sludge. It has been indicated by small scale testing that the sludge in the secondary clarifier with the addition of the aluminum or iron coagulants to the mixed liquor will settle to a total solids concentration of 1.0 to 2 percent, while without the chemical addition it will settle to about 0.5 to 1.0 percent*(30)*. Presumably, performance would vary with water characteristics and amount of coagulant.

A full-scale field test was made at a trickling filter plant which involved adding sodium aluminate to the filter influent to accomplish phosphorus precipitation*(31)*. It was not felt that adding alum would be desirable because of the poor mixing and essentially "plug-flow" in a filter, which in an insufficiently buffered wastewater could cause a drop of pH that would be too low for optimum biological activity. No adverse effect on the performance was noted when using aluminate. However, the phosphorus removal efficiency was not as good as that when a comparable dosage of alum was added to the aeration basin of an activated sludge plant. The sludge in the final clarifier had the same volume as before the chemical addition, indicating some densification.

4.6 SLUDGES FROM NEW TREATMENT PROCESSES

There are several new treatment processes which are coming into use; some have been studied sufficiently and are being incorporated into plants now under design, while others are not as fully developed and some are still in pilot plant stage.

The new processes or combination of existing processes that are of principal significance in municipal wastewater treatment, especially if organic industrial wastes are also being treated, include:

The Physicochemical Process: This is a nonbiological process involving treatment of raw wastewater with lime, alum, or iron salts, and possibly polymers in a unit or units including mixing, flocculation, and settling. Lime has been used because it removes phosphorus, complexes and precipitates any heavy metals, and at pH values below about 10.5 produces a dense sludge that thickens and dewaters readily. There are at present (December 1972) some 30 municipal plants under design, varying in capacity from 1 to 60 mgd, which will use the physicochemical process. After chemical treatment and settling, the effluent may go directly to activated carbon columns or to dual-media (coal-sand) filters for suspended solids removal. If lime is used, recarbonation precedes filtration. When low hardness waters are treated with lime and the pH is raised to above 11, recarbonation precipitates sufficient calcium carbonate so that a second chemical reaction unit is used. After filtration the wastewater is passed through granular activated carbon columns, which may be of either the downflow or upflow type. The advantages and disadvantages of each are discussed in detail in the literatue*(32,33,34,35)*.

The total weight and volume of sludge produced in the physicochemical process will usually be about the same as that produced in a conventional primary-biological plant. The sludges will be similar to those described in Section 4.4. These sludges may require smaller amounts of conditioning chemicals to dewater than biological sludges. However, their final disposal may or may not be any more simple or more economical (see Section 10).

The filters and carbon bed (if of the downflow type), when backwashed, will produce a liquid sidestream that has about 200 to 500 mg/l of suspended solids which will be fairly dense and settleable, and this stream will have to be recycled to a clarifier for solids separation.

Concurrent Biological and Activated Carbon Process: This process involves the use of powdered carbon mixed with the activated sludge. Currently (1973), there is no municipal wastewater treatment plant utilizing this process. The method could have merit where a considerable amount of soluble organic matter with low biodegradability is present from industrial wastes. There are some plants in operation treating industrial wastes*(36)(37)*. The activated sludge and the carbon settle in the clarifier to 2 to 3 percent solids (exclusive of the carbon). The powdered carbon is not regenerated or separated from the organic sludge, which dewaters with little or no conditioning.

Because of the lower cost of powdered carbon as compared to granular, the economics overall are competitive with other treatment process costs.

4.7 SEPTIC TANK SLUDGE (SEPTAGE)

The disposal of the sludge from septic tanks (septage) is a continuing problem, especially in parts of the country where no large municipal plants exist. Septic tanks are pumped out by private tank-truck operators who then dispose of the sludge in various ways, frequently without authority to do so.

In a survey made in Indiana about 10 years ago*(38)*, wastewater plant operators were asked regarding their policy of allowing discharge of septage into their sewerage system or treatment plants. About one-half of some 100 replies stated that they permitted such discharge. The other half said they did not permit such a practice, but there was no explanation of where the septage was discharged.

The sludge from septic tank cleaning, when discharged into the inflow of a treatment plant, can impose a shock loading of BOD and suspended solids, together with a high concentration of ammonia and probably some sulfides. Such discharges have upset the performance of primary clarifiers, caused odorous conditions, and adversely affected the secondary plant. The solids loading to the digesters can be significantly increased. This condition has been reported by many operators of small plants located in areas where a large number of septic tanks exist. Uncontrolled discharge of septage into small treatment plants not designed to treat such wastes is not desirable.

Some pretreatment and equalization of the discharge of such septage should be practiced, especially if the amount is large and the plant is relatively small. There is little specific information available regarding pretreatment of septage*(39)(40)*. Such liquid can have solids that are in various stages of anaerobic decomposition. If such septage were discharged into a covered holding tank and then pumped at a low rate to the treatment plant, the adverse effects could be minimized. Odors emanating from such a holding tank could be suppressed to a large degree by adding lime to raise the pH to about 11. Lime addition would react with any hydrogen sulfide and the odorous volatile acids. In addition, a high degree of pathogen kill and inactivation would be obtained. The sludge could be aerated after the lime addition.

The situation is complicated because households having septic tanks are usually not part of the municipality or political unit which financed the building of the sewerage system and treatment plant. In some areas there is a larger population using septic tanks than is connected to the sewerage system and public treatment plant. Certainly, those who have septic tanks and the private contractors who clean such tanks must pay a fee if they expect a treatment plant, which they did not pay to build or to operate, to handle their septage. This is a matter that may warrant some sort of regional control. Septage is a serious problem in some areas and requires prompt and positive action, if existing and even newly built wastewater treatment facilities are to perform as required at all times.

5. SLUDGE STABILIZATION

Before sludge can be disposed of, it must first be treated to reduce any adverse impact on the receiving land, air, or ocean. The term "sludge stabilization" is used to describe those methods which will reduce the detrimental impact of sludge disposal, i.e., render the sludge as innocuous as practical. Though stabilization has a specific technical meaning, in this report it involves other items. The following are the primary requirements for stabilization:

1. The highly volatile portion of the sludge is either removed or so treated that rapid decomposition, with resultant rapid oxygen consumption and the creation of odors, does not occur.
2. Any toxicants are in a form which would not immediately and adversely affect the environment. For example, organic toxicants, if not degraded, should have been altered in composition so their toxicity has been largely eliminated. Heavy metals should be complexed or rendered insoluble in water. (However, changes in pH after disposal may eventually cause heavy metal solubilization.)
3. A high degree of kill or inactivation of various types of pathogens should be attained.

5.1 BIOLOGICAL METHODS

5.1.1 Anaerobic Digestion

Water Pollution Control Federation Manual of Practice No. 16 should be referred to for a description of this process and the various design and operational considerations.

Anaerobic digestion involves biological decomposition of organic material in an environment devoid of dissolved oxygen. Decomposition results from the activities of two major groups of bacteria. One group is the "acid-formers," many of which are facultative. In the absence of free dissolved oxygen, they convert carbohydrates, fats, and proteins to organic acids, alcohols, and CO_2. Amino acids are broken down to ammonia. The other group is the methane bacteria which convert organic acids and alcohols to methane and CO_2. These latter bacteria are somewhat slow-growing and are sensitive to various toxicants, such as heavy metals and chlorinated hydrocarbons. They cannot grow in the presence of any free oxygen in the liquid, and their optimum temperature is between 85° and 95° F. Below about 70° F, their activity practically ceases. The acid-formers are not nearly as sensitive to an adverse environment.

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Good anaerobic digestion reduces the volatile matter by 40 to 65 percent. The remaining solids settle out so that their concentration by weight is not much less than their concentration in the raw sludge fed to the digester, and is frequently higher. Anaerobic digesters must be at a temperature of 85° to 95° F, which requires heating except in tropical climates. In the past they have been single stage or two stage. In the two-stage system, the liquid in the first-stage unit, where the active biological decomposition takes place, is usually continuously mixed by gas-lift circulation, pumped recirculation system, or mechanical mixers.

In the second-stage unit, there is no direct requirement for heating or mixing (although the equipment should be provided for operational flexibility); instead, a quiescent condition is provided which leads to the settling out of the solids and formation of a supernatant. In general, the digestion proceeds for about 30 to 60 days. After equilibrium, the solids are allowed to settle and are periodically removed for dewatering. Under current practice, the supernatant is normally sent back to the biological treatment plant because it is high in BOD, fine suspended solids, and nutrients; however, such a practice must not degrade the final effluent. Otherwise, the supernatant should be given proper separate treatment. The settleable solids can be dewatered on sand beds without further conditioning, though for dewatering by mechanical equipment digested sludge is further conditioned by chemicals or heat.

The combined volume of supernatant and settled solids discharged should be somewhat less than the inflow, since some of the solids are converted to methane and CO_2 and escape the digester. However, the weight of solids discharged should be significantly less than that of raw sludge fed, since an appreciable portion of the original volatile solids has been liquified and gasified. Of course, if the digested solids settle properly, as they should under suitable operating conditions, their volume should also be less than that of the raw sludge fed to the digester.

The destruction of the volatile solids results in the conversion of the organic nitrogen to ammonia, which remains in solution as ammonium carbonate. As a result there is a substantial increase in the alkalinity of the liquid. The phosphorus is released into the solution as some form of phosphate, together with other inorganic residues.

Anaerobic digesters are susceptible to upsets, primarily due to the sensitivity of the methane-forming organisms to variations in environment and toxicants in the sludge. Heavy metals, phenolics, and chlorinated hydrocarbons will inhibit the action of these organisms, resulting in an accumulation of organic acids and a resultant drop in the pH. The kinetics of anaerobic digestion are discussed by Pfeffer, *et al.(41)*. Hindin and Dunstan studied, under controlled laboratory conditions, the factors that can cause improper operation of digesters*(42)(43)*. The "loading" of a digester can be expressed in two ways: hydraulic loading (detention time), and solids loading (usually expressed as pounds of volatile solids per cubic foot of digester per day). Hindin and Dunstan studied the effect of both by using the same sludge but changing its concentration, either by dilution or by centrifuging. The important information they obtained is as follows.

With a detention time of 33 days, increased solids loading had these effects:

1. Increase in volatile solids
2. Increase in alkalinity
3. Increase in suspended solids (nonsettleable) in supernatant.

With a constant solids loading of 0.075 lb/cu ft/day of volatile solids, a decrease in detention time had these effects:

1. Increase in volatile acids
2. Increase in BOD and suspended solids in supernatant
3. Decrease in pH, alkalinity, and ammonia
4. Increase in odor of supernatant.

It is thus apparent that digester design criteria depend both on sufficient detention time and proper solids loading. The inflow solids concentration to the digester determines which factor is critical. The above investigators found that 30 days' hydraulic detention time was a critical value and that the loading should not exceed about 0.075 lb/cu ft/day of volatile solids.

There is a natural buffering system in a digester, due to the ammonium carbonate, volatile acids, and CO_2. For example, a decrease in ammonia (because of decreased detention time) can cause a digester to become acidic. Another important factor which also depends on sufficient detention time and proper solids loading is the affinity between the suspended solids and the liquid. The solids are lyophilic due primarily to the proteins and colloids. With a sufficient digestion time, the proteins are degraded and colloids decomposed. The solids are then lyophobic—they have a greatly decreased affinity for the liquid and will settle.

High-rate digestion of primary and activated sludge has been successfully practiced, but operations must be strictly controlled. Zablatzky and Baer describe the necessary controls thoroughly*(46)*, such as complete mixing, uniform feed, and frequent monitoring of volatile acid, alkalinity, and pH. The loading for high rate digestion is 0.10 to 0.40 lb of volatile solids per cu ft/day and the hydraulic detention time is 15 to 20 days. The completely mixed contents are discharged into a second unit for supernatant separation.

Some field experiences indicate that mixtures of primary and activated sludge are extremely difficult to settle and to obtain filterable concentrations of solids after anaerobic digestion *(44)(45)*. A review of studies involving digestion of activated sludges invariably indicates that a poor quality of digested sludge was obtained because the basic criteria controlling anaerobic digestion, as discussed above, were not followed in the design and operation of the digesters. In addition, it is important that activated sludge be thickened before being pumped to a digester (see Section 6). It has been the general experience that separate thickening of the activated sludge is preferable to return of the waste activated sludge to the primary clarifier.

Stanbridge *(47)* and others *(48)* have made extensive tests involving digesting and dewatering primary sludge, mixtures of primary and activated sludge, and activated sludge alone. The results are important, since all the sludges could be dewatered satisfactorily. It was concluded that digested activated sludge dewatered less readily than a mixture of primary and activated and required more chemical conditioner; separate thickening of the excess activated sludge ahead of digestion was effective, and a smaller proportion of the volatile matter was destroyed when activated sludge was digested than when primary sludge was digested. To obtain a well-settling digested activated sludge, a detention time greater than 20 days was necessary.

From a practical operational standpoint, one of the most common and troublesome problems of anaerobic digesters is cleaning the grit and other heavy solids that accumulate at the bottom. If the solids are not removed, they gradually decrease the digester volume. Good mixing in the digester will reduce the frequency of cleaning and is desirable in any case. However, the design engineer should provide properly sized and accessible openings so that settled solids can be easily removed by high pressure water streams, for instance. This is discussed in detail in Manual of Practice No. 16 of the WPCF.

Cleaning of the digester may put the unit out of operation for several days. The two-stage system could provide a means of continuing digestion when there is only one primary digester and it is inoperative. Of course, heating and mixing would have to be provided for the secondary digester in that case. The two-stage system, in addition to providing, normally, a long settling time so that the suspended solids can be reduced to a minimum in the supernatant, can provide more foolproof operation and a "backup" system when the primary unit is not operating. It has generally been noted that a better quality supernatant and better overall operation, as far as solids settling is concerned, are obtained if two-stage digestion is used. Considering the frequent upsets and other problems that digesters are prone to, it is an expense that is worthwhile, especially for high-rate digester systems.

5.1.2 Aerobic Digestion

Aerobic digestion is less sensitive to toxicity than anaerobic digestion. If sludge temperatures below 50° F are to be encountered for any length of time, increased retention time should be sludge in a tank that is usually uncovered and unheated and has a depth of 10 to 20 ft. The principal operating cost is the power required for aeration. The sludge is supplied with oxygen so that a dissolved oxygen concentration of at least 1 mg/l exists in *all* portions of the basin. The aeration can be accomplished by means of compressed air and porous diffusers, surface-type mechanical aerators, or submerged turbines supplied with compressed air (or oxygen). However, with relatively thick sludges, it may be almost impossible to dissolve and distribute oxygen throughout the entire sludge mass unless a mechanical device is used.

Aerobic digestion is less sensitive to toxicity than anaerobic digestion. If sludge temperatures below 50° F are to be encountered for any length of time, increased retention time should be provided. Normally, a 10- to 15-day retention time is sufficient to stabilize the sludge and accomplish a reduction in volatile solids of about 30 to 55 percent *(49,50,51)*. If the temperature of the liquid drops to around 40° F, the retention time should be increased to 25 to 30 days. Aerobic activity of some degree has been observed down to freezing temperature. Biological oxidation generates heat and, for thick sludges having a high volatile content, excessive temperatures can be produced if heat loss from the unit is insufficient*(52)*. Oklahoma State University has carried out and reported on some extensive tests on aerobic digestion*(53)*. Though sometimes unexplained and erratic results were obtained, in general, aerobic digestion was effective in improving the drainability of the sludge. The dewatering characteristics of aerobically digested sludge are usually similar to those of anaerobically digested sludge*(54)*. Cameron reported recently on aerobic digestion of waste activated sludge to improve its filterability*(55)*.

The oxygen requirements are about 10 ppm/hr/1,000 ppm of volatile solids in the digester. However, if primary sludge is digested with secondary sludge, the oxygen requirements will increase by 50 to 100 percent above the 10-ppm/hr figure. If compressed air is used with porous diffusers, about 25 to 35 cfs/min/1,000 cu ft of digester volume should be sufficient. If aerobic digesters are to be used in cold climates, care should be taken to keep the temperatures above 40° F, and the detention time should be about 30 days. Also, in freezing climates, or where it is difficult to maintain a proper temperature in the digester, surface-type mechanical aerators should not be used. Either compressed air with diffusers or a submerged turbine supplied with compressed air should be used in such cases. In cold climates, the units should be protected from heat loss. Care should be taken that all solids are kept in suspension and the digester liquid is well mixed, and that the proper dissolved oxygen level is maintained. There are, of course, no odors generated from a properly operated aerobic digester.

As with anaerobic digestion, when the liquid portion is returned to the treatment plant, it results in a pollutant load which would not be imposed if the sludge had not been "digested." In the case of aerobic digestion, there is very little BOD load imposed, but the nonbiodegradable, or poorly biodegradable, organic solubles as measured by COD or TOC are increased. More importantly, a large portion of the nitrogen and phosphorus is solubilized and oxidized to nitrates and phosphates, which results in increased costs if they are to be removed from the effluent. The fine suspended solids in the supernatant can be fairly high, since prolonged aeration causes deflocculation.

Mixtures of primary and secondary sludge may be stabilized if sufficient agitation is provided. With primary sludge, it is possible for grit and other heavy inert solids to enter the unit. Therefore, the basin must be designed for easy cleaning and removal of the heavy solids which will not be kept in suspension. It is good practice to have at least two basins so that one could be out of service for a few days and some digestion achieved in the second basin. Also, the second basin can serve the same function as the second-stage anaerobic digester tank; that is, accomplish liquid-solids separation, but be equipped with aeration so that in an emergency it can perform as a digester.

5.1.3 Composting

Composting is an aerobic, thermophilic, organic sludge stabilizing process. The thermophilic organisms grow best in the range of 130° to 165° F.

Dewatered sewage sludge—about 79 percent moisture—has been composted in a specially designed unit*(56)*. The reduction in total solids was 30 percent and volatiles were reduced by 47 percent. No pathogens could be detected in the final product, even with massive inoculations of the raw sewage. The sludge is completely stable and does not attract insects, so it can be readily disposed of on land or used as a soil conditioner. Since the process is aerobic, almost all the ammonia is either oxidized to nitrates, or goes off as a gas.

5.2 CHEMICAL METHODS

The principal chemical process that can stabilize a sludge in accordance with the previous definition of stabilization is the application of lime to obtain a pH of 11.5. It has been known for some time that applying lime to organic matter and raising its pH to above 11 will cause complex changes in the volatile solid matter, especially when the sludge is dewatered. If placed on the land, putrefaction will be suppressed for a considerable time and then, as the pH drops, gradual decomposition of the organic matter will occur with considerably reduced generation of odors. Furthermore, at pH of 11.5, the destruction of pathogenic organisms is practically total. The evidence is strong that at such pH virus inactivation can occur*(57)*. Although there is no good evidence as yet with regard to destruction of dormant cysts, worms, and spores, nevertheless pathogen destruction in a few hours is greater than that accomplished by the anaerobic or aerobic digestion process over a period of several days.

A detailed study was recently reported on lime stabilization of primary organic sludges and mixtures of organic and inorganic sludges by the AWT Laboratory of the EPA in Cincinnati*(58)*. To ensure maximum pathogen destruction, it was found desirable to add the lime to the sludge over a period of time until the pH stabilized at about 11.5. It could then be dewatered on a sand bed or a vacuum filter. No further conditioning of the sludge was necessary. The amount of lime required will depend on the chemical composition of the wastes and whether the raw sewage had been treated with alum or an iron salt to increase the solids capture in the primary basin. For raw sewage sludge, the lime cost would be about $2/ton of dry solids; if the sludge had been treated with alum, the lime cost would be about $4 to $5 per ton of dry solids; with previous lime treatment, the cost would be $2.5 to $3 per ton. A sludge cake with such lime treatment could be disposed of in a properly operated landfill.

Another chemical treatment that has been used recently to stabilize sludge and enhance its dewatering characteristics is the addition of large dosages of chlorine. The equipment for this proprietary process consists of a pressure tank and recirculating pump. The chlorine is applied to the raw sludge, which is pumped into a pressurized holding tank under about 45 psi and held there for 10 to 15 minutes*(59)*.

The studies were initially made in the laboratories of the Passaic Valley Sewerage Commission, Newark, New Jersey. The investigator found that, by adding 500 mg/l of chlorine per each percentage solids concentration of an organic sludge, he was able to eliminate odors and the color of the sludge changed from black to light tan. This chlorine dosage also increased the drainability of the sludge.

Chlorination depresses the pH, and this should be corrected by adding an alkali. If sodium hypochlorite is used, no significant change in pH occurs. At a dosage of 500 mg/l and a sludge with 1 percent solids, 100 lb of chlorine are needed per ton of dry solids.

At the outlet of the reactor, the residual is about 10 mg/l at the 500-mg/l dosage, and 200 mg/l at double this dosage. No information has been reported regarding how this residual changes and in what form it exists. Because of the high ammonia-nitrogen content of sewage sludge, most of the residual is probably in the form of chloramines, at least initially.

The chlorinated sludge is reported to be stable and to dewater on a sand bed without giving off any odors. Before vacuum filtration or centrifugation, the sludge may require some further chemical conditioning. No installations involving such mechanical dewatering are known at present. It would appear that proper neutralization of the sludge, probably with lime which could further condition it, would be essential before mechanical dewatering. It seems reasonable to expect that the liquor resulting from such chlorine treatment of the sludge may have many types of chlorinated organics in solution, in addition to chloramines. The toxicity to fish life and other aquatic life of this liquor, even in low concentrations, must be considered.

Either recycling the liquor to the plant biological treatment process or treating the liquor separately must be carefully studied and evaluated. Any chlorine-complexed organics may have to be removed, and close attention must be given to the biodegradability of the liquor and its effect on the plant.

Disposal of the dewatered sludge solids in landfills may be possible, though no information appears to exist regarding the characteristics and composition of any leachates from such sludge. Before heavy chlorination is used for sludge treatment, consideration must be given to the plant effluent, the effect of the sludge liquor when returned to the treatment plant, and the composition of leachates from sludge disposal sites. No information has been found on the composition of the solubles in the liquor. Recently, a small treatment plant was designed for Delhi, New York, which will use this process to treat the sludge. The sludge will be dewatered on sand beds*(62)*.

5.3 PHYSICAL METHODS

The only practical sludge stabilization method that can be considered as being essentially "physical" is heat treatment. However, this term is probably not too accurate, since during the heat treatment there are changes in the composition of the organic matter—some solids are solubilized, and in one of the heat treatment processes, which adds a small quantity of air to the reactor, some oxidation occurs. This process is discussed in more detail in Section 8.2. Since the temperature of about 350° to 400° F can destroy pathogens and can degrade a large portion of the volatile solids, the final sludge is considered stabilized and can be disposed of on the land or in a landfill after dewatering.

Pasteurization (150° F for about 1/2 hr) of liquid sludge has been considered in this country and is practiced at several localities in Germany. It destroys pathogens to a high degree, but does not stabilize the sludge since it does not reduce the volatile solids.

6. SLUDGE THICKENING

6.1 GRAVITY

Gravity thickening is the most common sludge concentration process in use at wastewater treatment plants. Suspended solids particles with a sufficiently great settling velocity may be separated from water by maintaining quiescent conditions. Gravity thickeners usually follow gravity clarifiers, sometimes in the same unit, but the emphasis is on removing water from solids rather than solids from water. In thickening, the predominant mechanism is hindered settling rather than free settling typical of clarification. An advantage of gravity thickening is its simplicity. However, gravity thickening does not produce as highly concentrated a sludge in some cases as do other thickening processes.

In a primary clarifier, the settled solids can thicken sufficiently under the right conditions without any further treatment. Sometimes a coagulant or an organic polymer is added to aid the removal of the finer and colloidal solids that do not normally settle out. Inorganic coagulants also can precipitate phosphorus. Primary clarifiers for sewage are usually designed for average hydraulic loadings of 1,000 to 1,500 gpd/sq ft. They can be either circular or rectangular and must be equipped with skimming devices.

The clarifier following a biological treatment process must handle much lighter solids, and therefore the hydraulic loading averages only about 600 to 700 gpd/sq ft and should not exceed 1,200 gpd/sq ft for peak flows, especially if activated sludge is handled. Such clarifiers accomplish a certain amount of thickening of the sludge that settles out. The sludge from a trickling filter plant will normally be concentrated to about 3 to 4 percent by weight. However, activated sludge rarely concentrates to more than 0.5 to 1 percent in final clarifiers, except in systems where pure oxygen is used, and then concentrations of 2 to 3 percent have been obtained.

To thicken the secondary or mixture of primary and secondary sludges further, either before digestion or dewatering, the sludge can be pumped to a separate gravity thickener. These units have hydraulic loadings of about 200 to 500 gpd/sq ft. Solids loadings are about 8 to 20 lb/sq ft. The retention time cannot be too long if the liquid temperature is, say, 80° F or higher because anaerobic conditions quickly develop with resultant gassing and floating of the sludge. Gravity thickening is not too effective for waste activated sludge alone. Usually, it can only increase the solids concentration from about 1 percent to 3 percent by weight or, in oxygen plants, to about 5 to 6 percent. Also, if nitrates are present, denitrification could occur with release of nitrogen gas bubbles, which will result in floating of the biological sludge floc. Chlorination of the sludge in the thickener is frequently used to suppress or delay anaerobic conditions and denitrification, as well as to control odors.

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One factor that can cause poor thickening and even flotation of light biological sludge particles, especially activated sludge floc, is saturation of the liquid portion of sludge with nitrogen gas because of exposure of the wastewater to the atmosphere or to aeration. Changes in pressure or temperature that decrease the solubility of nitrogen can cause it to come out of solution in the form of small bubbles which attach themselves to the sludge particles. Any biological denitrification would aggravate this problem.

The required surface area of the thickener may be estimated from a solids settling rate test made in a 2,000-ml graduate. The surface area must be large enough that the upward velocity of liquid leaving the basin is not greater than the settling velocity of the slowest settling particle which is to be captured. Sparr states that experience has shown that gravity thickeners for activated sludge alone should have a solids loading of about 5 to 8 lb/sq ft/day and 6 to 10 lb/sq ft/day when primary sludge is mixed with activated sludge*(61)*. These are loadings for thickeners having stirring pickets on the scraper trusses, and can be increased if chemicals are added.

There are varied opinions regarding whether activated sludge should be gravity thickened alone or whether the primary sludge should be mixed with the waste activated sludge in the thickener. Sparr *(61)* reports that experiences of Torpey in New York City show very definitely that by mixing the two sludges in the thickener many problems associated with thickening of waste activated sludge alone can be eliminated. The heavier primary solids fill the voids in the light, flocculant activated sludge. Torpey has obtained solids concentration in the combined thickened sludge of 4 to 6 percent by weight.

Conventional thickening tanks are usually circular with a cone-shaped bottom and center drawoff. The concentrated sludge is removed from the bottom and the overflow liquor is drawn off for return to the plant inlet. The tanks are about 12 to 15 ft deep (sometimes 10 ft for small plants), with inlet facilities that dissipate the entrance velocities, and a single outlet pipe with short suction connections.

A common thickener consists of a circular tank with rotary collector arms equipped with vertical "pickets" which gently agitate the sludge. The action of the pickets releases the water bound in the sludge particles and also any gas bubbles. Blades on the bottom of the collector arms move the concentrated sludge to a center drawoff point. A skimming arrangement should be installed.

The liquid overflow sidestream from sludge thickeners is returned to the plant after the primary clarifier. The soluble organic and inorganic matter contained in the sidestream should not be significantly different from that of the biological process effluent, unless tertiary treatment will be carried out. It is good practice to return this overflow to the head of the secondary system, since the suspended solids, which may range from 100 to 1,000 mg/1, are not settleable in the time available in a primary clarifier and the overflow may cause other problems. Any thickener overflows will, of course, increase the suspended solids and associated BOD loadings on the secondary plant and must be considered as a cost attributable to the sludge handling process of the plant.

The quantity of overflow from gravity thickeners appears to vary considerably from plant to plant, depending on loading and sludge type. At Grand Rapids, Michigan, the overflow amounts to about 0.3 percent of the plant flow*(62)*, while the overflow at the Bowery Plant in New York City averages about 5 percent of the plant flow *(63)*. The difference in quantities of overflow is explained by the difference in thickness of inflow sludge. There are instances where returning thickener overflow has caused operational problems. Such problems can occur when septic or bulky sludge will not thicken and the resulting overflow contains high concentrations of suspended solids and BOD. Jordan and Scherer*(64)* reported that recycling overflow from a gravity unit that was thickening a bulking activated sludge resulted in a buildup of suspended solids in the aeration tanks at Amarillo, Texas, with resultant carryover in the final effluent.

6.2 PRESSURIZED-AIR FLOTATION

Flotation, like gravity settling, can be and has been used for clarification or removal of suspended solids from the main wastewater stream. Like gravity settling, it has been adopted for thickening waste sludges, especially organic sludges (such as waste activated sludge) that do not thicken readily by gravity settling. To accomplish good thickening, and also to have a relatively clear underflow, the raw sludge is frequently "conditioned" with either an organic or inorganic coagulant.

The particular flotation process described here is referred to as dissolved-air or pressurized-air flotation. A volume of relatively clear water (usually the underflow) is pressurized to 30 to 70 psi and air is injected into the pressurized liquid so that dissolution occurs. Various schemes are used to inject a large amount of air into solution, though rarely does it approach about 75 percent of saturation, corresponding to the theoretical value for the pressure and liquid temperatures.

This pressurized liquid is then released through a specially designed valve at a pressure equal to the hydrostatic head in the flotation basin (about 3 to 4 psi) and mixed with the raw sludge. The drop in pressure causes microscopic air bubbles to come out of solution and attach themselves to the sludge particles or floc, and thus rapid flotation results. Waste activated sludge having a concentration as it comes from the final clarifier of 0.5 to 1.0 percent by weight of solids can be readily thickened to 4 to 5 percent. It is then suitable for dewatering with a vacuum filter, centrifuge, filter press, etc. The suspended solids capture can range from 83 to 99 percent, depending on loading and usage of polymers. Such flotation thickening of activated sludge can also be used ahead of anaerobic digestion.

The two important design criteria are: (1) solids loading, on the basis of pounds of dry solids per square foot of clarification area in the flotation basin, and (2) the air to solids ratio. It has been found that the weight of air that is dissolved averages about 1 percent of the dry solids applied. The solids loading may range from 1 to 2 lb/hr/sq ft. Some activated sludge may require a polymer for the higher loading. The hydraulic loading should not exceed about 1.0 gpm/sq ft. The above criteria are for thickening of waste activated sludge *(65)(66)*. One of the advantages of using air flotation for thickening a sludge, especially activated sludge, is that the system is kept aerobic. This eliminates septic action and "gassing" in the sludge, which frequently happens in gravity-type thickeners due to anaerobic decomposition.

Flotation can be used to thicken various types of sludges, including inorganic sludges such as metal hydroxides. Bench-scale test units are available for testing of any sludge to determine the necessary design parameters for sludges which are different from those normally produced in a domestic wastewater treatment plant.

It has been reported that flotation thickening without chemical addition has recovered between 83 and 95 percent of the solids, based on average values for seven treatment plants

(67). Ettelt *(68)* also found that polymer addition increased the capture from 92.7 to 99.6 percent.

Flotation thickener liquor can be recycled to the secondary plant. Ettelt recorded the solids concentration in liquor from thickening activated sludge without chemicals as between 800 and 1,000 mg/l. The liquid underflow, and also the sludge in a pressurized air flotation unit, has, of course, a high concentration of dissolved oxygen, which prevents any septicity.

6.3 CENTRIFUGATION

Centrifuges have been used in the wastewater treatment field primarily for sludge dewatering (see Section 9.3); however, one type of centrifuge, known as the disk or nozzle type, is coming into use for thickening of activated sludge. The disk type centrifuge has been used for many years in the chemical process industry, but its use for sludge thickening in the field of wastewater treatment is relatively new and only a few installations exist *(69)(70)*. Its use at present is limited to waste activated sludge. The thickening efficiency of the disk centrifuge is comparable to that of the pressurized-air flotation system. The principal advantages of the disk centrifuge are compactness, overall lower total costs, and improved solids capture without chemicals. There is a risk of clogging if proper screening equipment is not used and maintained ahead of the centrifuge.

The sludge passes through nozzles about 0.1 in. in diameter due to the pressure produced by a "g" value of 5,000 and greater. It then flows out of the unit. The sludge entering the unit must be degritted by a hydrocyclone, if effective grit removal does not occur in the treatment plant, and at least one self-cleaning screen should be installed ahead of the centrifuge to remove any particles (such as hair or string) in the liquid larger than the smallest openings in the unit. If there are large amounts of this material, two screens should be provided. The thickened sludge can go to a digester or to other processing for eventual dewatering. The solids capture in a disk centrifuge, when using a polymer, can be on the order of 95 to 98 percent with a moisture content of about 4 to 5 percent. Capture of 75 to 95 percent has been obtained without chemical addition.

The centrate can be returned to the aeration basins if evidence indicates that the solids can be entrained in the main portion of the MLSS*(70)*. The liquid from the self-cleaning screen should be returned to the primary clarifier. If most of these screened solids are not captured in the primary basin, this sidestream must be disposed of with the thickened sludge; otherwise, the screenings will build up in the system. Screenings in the thickened sludge reduce the solids concentration only slightly, since the stream is only a small percentage of the main liquid sludge stream.

7. SUPERNATANTS FROM BIOLOGICAL DIGESTERS

In the sludge digestion or stabilization process, whether anaerobic or aerobic, the solids volume is decreased because the volatile solids are destroyed by conversion to gases, water, and soluble residues. The remaining solids will settle, if the process has been carried out properly (refer to Section 5.1), leaving a supernatant which must be removed and disposed of in some manner. These solids should concentrate to approximately the same percentage solids as the raw influent sludge. The supernatants have a high concentration of soluble and insoluble pollutants and a volume which can average about 1 percent of the raw wastewater treated. Handling and disposal of supernatants can present some serious problems in the overall plant performance.

7.1 ANAEROBIC DIGESTER SUPERNATANTS

Anaerobic digester supernatants vary considerably from plant to plant. It has been noted that supernatants vary from clear, through shades of yellow, to black*(71)*. The odor may be acceptable or very offensive and nauseating. It may be relatively weak liquor, or its strength may be extremely high in terms of the raw wastewater.

Several factors which affect supernatant quality include the type of sludge treated, the design of the digester, and the method of operation*(72)*. Plants treating primarily domestic wastes produce a weaker supernatant than plants treating wastes containing large percentages of organic type industrial wastes. It was also observed that a raw sludge with a high volatile content will produce a supernatant with higher solids content than a raw sludge with a low volatile content. Short digestion periods of 10 to 15 days have been found to leave more solids in the supernatant*(73)*. It has also been noted*(74)* that supernatant from primary plants is generally weaker than supernatant from secondary plants, but there is considerable variation among plants of each type. Indeed, variation in supernatant quality for a particular plant is not unusual*(75)*.

Table 3 presents data on supernatant characteristics according to plant type*(75)*. These data show that supernatant from primary plants is, on the average, weaker than the other supernatants, but there is considerable overlap.

The quantity of supernatant varies less than the quality. Generally, the quantity will range from 5,000 gal. per million gallons (mil gal.) of sewage treated for primary plants to 10,000 gal. and more for activated sludge plants, with trickling filter plants falling in between. A conservative figure to use for activated sludge plants is 1 percent of the wastewater flow.

TABLE 3. SUPERNATANT CHARACTERISTICS FROM ANAEROBIC DIGESTERS (ALL VALUES IN MG/L)

	Primary Plants	Trickling Filters*	Activated Sludge Plants*
Suspended solids	200–1,000	500–5,000	3,000–10,000
BOD	500–2,000	500–5,000	1,000–8,000
COD	1,000–4,000	2,000–10,000	3,000–15,000
Ammonia (NH_3)	300–400	400–600	400–1,000
Total phosphorus as P	50–200	100–300	300–700

*Includes primary sludge.

Recycle of supernatant to the plant will have no significant effect on the plant hydraulics. Such recycling can, however, affect other portions of the plant operation, such as aeration requirements, chemicals required for coagulation, phosphorus removal, ammonia removal, and the final effluent quality in general. Plant operation is affected not by the supernatant volume but by the mass of constituents in that volume. For some constituents, the amount in the supernatant is negligible compared with the amount entering the plant, but for other constituents the amount of supernatant is substantial. Malina and DiFilippo*(75)* reported that the amount of nitrogen in the supernatant of the Archibald, Ohio, activated sludge plant was about 40 percent of the nitrogen in the plant influent.

Returning digester supernatant to the head of a plant can produce several problems. In some cases, supernatant return has caused the primary tanks to become septic and emit odors. The sludge from these tanks also becomes less concentrated. Supernatant return can cause additional problems in secondary plants. Clogging of trickling filters can occur, and odor problems can arise because of the release of dissolved gases as the primary effluent is applied to the trickling filters or is aerated in activated sludge plants.

Returning supernatant will increase operating costs. The added load increases the chlorine demand in prechlorination. Greater quantities of chemicals are required for chemical coagulation. All such costs are attributable to sludge handling and disposal.

Supernatant addition can cause periodic upsets in biological treatment processes. Also, supernatants have high soluble COD values, a portion of which is not readily degraded biologically. Because of upsets, and because treatability is affected, discharge of organics to receiving waters is increased.

The above problems seem to dictate against recycling supernatant in a treatment plant; however, some operators have found few problems from such recycling. The effect of recycling supernatant can be minimized by proper design of digester and adequate allowances in general plant design.

Many of the problems associated with recycling supernatant seem to be caused by the septicity of the liquor. Return of the supernatant to preaeration units has been found to be helpful, although this could cause release of odorous gases and volatile organic compounds.

Even though recycling supernatant does not appear to affect operation of many plants, and may reduce BOD and solids removal efficiency only slightly, recycling can greatly affect removal of nutrients by a treatment plant. It was found at the Archibald, Ohio, activated sludge plant that 57 percent of the nitrogen fed to the digester was returned as supernatant*(75)*.

It has been noted by Vacker, *et al.(76)*, that digester supernatant should not be recycled directly to treatment plants removing phosphorus by uptake in aeration tanks. The return of supernatant which has a high soluble phosphorus content (such as that from an activated sludge plant) will work against phosphorus removal, since it is the biological sludge which is the vehicle for removing phosphorus from the wastewater being treated. However, any phosphorus that is "tied up" chemically by aluminum or iron will, to a small degree, be released to the supernatant (see Sections 4.4 and 4.5). The only phosphorus released is that due to decomposition of the volatile organic matter.

The above discussion indicates that plants can and have been upset due to return of supernatant; however, there have been cases in which the effect has been minor. Nonetheless, the costs associated with removing pollutants that are present in the supernatant, and are limited in the final effluent, are attributable to the sludge handling process in the treatment plant.

A process was developed many years ago by Kraus of Peoria, Illinois, for handling wastes high in carbon but deficient in nitrogen. In the process, supernatant, which is rich in nitrogen, is aerated with some digested sludge and with part of the return sludge from the activated sludge plant and then returned to the aeration tank. The nitrogen content of the supernatant corrects the nitrogen deficiency, and the solids in the digested sludge improve the settleability of the mixed solids in the aeration basin. If the plant is designed for nitrification, the aeration nitrifies the ammonia in the supernatant.

7.2 SUPERNATANT TREATMENT—REDUCING ITS IMPACT ON PLANT PERFORMANCE

To reduce, or possibly eliminate, the adverse effect of recycling anaerobic digester supernatant to the treatment plant, there are several techniques or operational modifications that can be employed. Adequate thickening of sludges in settling tanks or in sludge thickeners ahead of digesters is important to reduce the volume of supernatant and obtain a more concentrated digested sludge.

When sludge is pumped into an unmixed digester, some disturbance of the digester contents occurs. In single-stage units there is a tendency for the solids in the supernatant to increase. It is generally agreed that pumping sludge to single-stage digesters at a uniform but low rate is preferable to pumping intermittently at high rates, but this is not always possible at small plants. The effect of pumping disturbance on the supernatant is substantially reduced in two-stage digestion.

High rate digesters can, and very frequently do, cause serious problems with regard to the quality of the supernatant and the thickening of the solids in the digester. In fact, there have been instances where the solids remained almost completely dispersed and did not thicken much above 2 percent by weight, which greatly increases the costs of dewatering. Such poor performance was attributed to the operation of a hydraulically overloaded digester, or, looking at it in another way, reducing the solids detention time below that required to obtain proper digestion. Elutriation has been helpful in obtaining improved thickening of the solids from such digesters. Of course, this has been at the expense of handling, usually by chemical coagulation, the fine solids in the elutriate.

Digester loading affects the quality of supernatant. Data show that digesters loaded at 0.40 lb volatile solids/cu ft/day produce supernatant about twice as strong in terms of suspended solids and about three times as strong in terms of BOD as digesters loaded at 0.10 lb volatile solids/cu ft/day. Burd*(1)* reports on a very interesting performance comparison between a high-rate and a standard-rate digester. The digestion time for the high-rate unit was 16 days and for the standard-rate unit was 30 days. The reduction in volatile solids was about 65 percent in both units. However, the settled digested solids in the standard-rate unit were 6 to 9 percent by weight and 3.5 to 4 percent by weight in the high-rate unit. It is not economical to dewater a thin sludge, as is well known. Short digestion times produce fine lyophilic solids which remain in the supernatant.

If high-rate digestion is to be practiced, it is essential that the incoming sludge be thickened to about 4 to 5 percent. The digester should be completely mixed and operation closely controlled. This means that excess activated sludge must be thickened by either pressurized-air flotation or the use of a disk-type centrifuge.

There are several possibilities for treating supernatants. Storage of the supernatant in lagoons for long periods to allow settling of the suspended solids is simple, but does require considerable land area and precautions to minimize leachate. The lagoons must be isolated to ensure that there are no odor nuisances.

Because of fly breeding and odor problems, lagooning is not recommended near residential areas. Howe*(73)* found that a detention time of 60 days decreased BOD, suspended solids, colors, and ammonia by about 85 percent. Hydrogen sulfide was diminished by 94 percent. Aeration of supernatant lagoons can provide additional treatment, but at the risk of increased odors.

Separate aerobic biological treatment of anaerobic supernatant by trickling filters and the activated sludge process has been studied. The Greater London Council, in their investigations*(48)*, studied the treatment of digested sludge liquor using coke as the trickling filter media. They investigated various dilutions of the supernatant with clarified plant effluent. A 1:1 dilution gave about 60 percent removal of ammonia and 85 to 90 percent BOD removal. The ammonia concentration was about 400 to 500 mg/l in the untreated supernatant. However, more studies are needed to establish precisely some of the design and control parameters.

Separate treatment of supernatant may be necessary at existing plants which are overloaded and producing poor quality effluents. An overloaded plant is likely to have an overloaded digester with resultant poor quality supernatant. Separate treatment of supernatant could be a temporary solution before the main plant can be enlarged and upgraded.

Phosphorus can be removed from supernatants by treatment with lime to raise the pH to about 9.0 to 9.5. The precipitates formed are various calcium phosphates and ammonium-magnesium-phosphate (NH_4MgPO_4), which is very insoluble at a pH above 9. Also, some magnesium phosphate will be precipitated, depending on the amount of calcium and magnesium cations which are present. The solubility of NH_4MgPO_4 is only about 160 mg/l at normal pH in pure water, and this is further reduced in the digester supernatant because of the ammonium ions present. This solubility is equivalent to about 20 mg/l expressed as phosphorus. The concentration of P in supernatants can amount to several hundred mg/l as P. A detailed study made by the Dearborn Chemical Division of W.R. Grace Co., supported by the EPA*(77)*, established the various treatments and conditions that are necessary to precipitate phosphorus from digester supernatants. The total precipitate will be a mixture of NH_4MgPO_4, calcium phosphates, and magnesium phosphates. If the calcium ion is low, the addition of a magnesium salt such as MgO or $MgSO_4$ will produce a precipitate that has high fertilizing value because of the concentration of nitrogen and phosphorus it contains. It can be used without concern about root or leaf "burning," since it dissolves very slowly.

Because of the low solubility of the NH_4MgPO_4 in digester supernatant, it forms supersaturated solutions, especially if there is a change in pH from evolution of CO_2, and will precipitate out as a hard scale on pipes and other wetted surfaces. The Hyperion plant at Los Angeles has experienced serious problems with such depositions*(78)(79)*. Of course, the problem would only be serious in hard water localities, especially those that have a relatively high magnesium hardness. The precipitation of the NH_4MgPO_4 can also be accomplished by heating the supernatant to about 65° C to decompose the ammonium bicarbonate present in supernatants, release the CO_2, and raise the pH.

The addition of lime or magnesium salts to precipitate the orthophosphates will also coagulate and remove a large portion of the fine suspended solids present in many supernatants, thus reducing the load on the treatment plant.

7.3 ELUTRIATION

The liquor in anaerobically digested sludge has a very high alkalinity, primarily from the ammonia generated during the digestion process. It also has a variety of organic and inorganic compounds such as phosphates and a high concentration of free CO_2, methane acids, and minor amounts of hydrogen sulfide.

In the mid-1930's, Genter *(80)(81)* proposed that the amount of inorganic chemicals (usually ferric chloride and lime or both) used to condition digested sludge before dewatering on a vacuum filter could be substantially reduced if the alkalinity of the liquor associated with the sludge could be lowered by the simple process of "diluting out" with fresh water or treatment plant effluent. He termed the process elutriation. Burd*(1)*, in his report on sludge handling, gives a detailed description of the process and its present status in the wastewater treatment field. Burd and others point out that Genter may not have fully realized that a major benefit of elutriation was the washing out of the fine unsettleable solids and not merely the reduction in alkalinity. Eliminating such fine colloidal-type solids from the settleable solids reduces the amount of flocculating (conditioning) chemicals required. These fine solids in the elutriate must be removed either by separate treatment or by recycling to the plant. Settling by itself is not the answer. Separation can be either by use of additional flocculating chemicals or by adsorption in the biological system, such as on the activated sludge.

The inability to settle solids in the digested sludge properly may indicate that elutriation would be helpful. However, it should be kept in mind that the nonsettleable solids present in the elutriate are the same nonsettleable solids originally present in the digested sludge, only they are now in a larger volume of liquid. It cannot be definitely assumed that these solids can now be removed by recycling the elutriate to the treatment plant. There have been many instances where such solids, because they could not be coagulated, have passed through a plant and out into the effluent. If they are captured in the plant, the BOD, suspended solids, ammonia, phosphorus, and any other pollutants that the elutriate contains must be considered as being a load over and above that imposed on the treatment plant by the raw wastewater. It may be necessary to treat the elutriate with additional chemicals to coagulate and settle the solids before the elutriate is recycled, or the chemicals can be added and flocculated and the suspension returned to the treatment plant to ensure solids capture. However, it should be kept in mind that mixing a liquid having flocculated solids with another stream of entirely different pH and other chemical characteristics can cause deflocculation.

Several plants*(44)(45)*l have experienced serious deterioration of their final effluent from recycling the elutriate. The fine solids in the recycled elutriate have degraded the effluent and caused odors. The basic problem is that the digestion process has created poorly settling solids (see Section 5.1.1). Biological treatment processes remove soluble and suspended pollutants by incorporation into settleable solids, which are then removed from the treated liquid by settling in a clarifier. The elutriation process redisperses solids so they become unsettleable, requiring the addition of chemicals to flocculate and agglomerate them.

Elutriation was incorporated in the Los Angeles Hyperion Plant, which had primary plus high-rate activated sludge treatment. The sludge was digested anaerobically. The digested solids would not settle sufficiently to dewater: to coagulate them required chemicals which cost $20/ton of dry solids (1958). With elutriation, chemical costs were substantially reduced, but about 50 percent of the solids were in the elutriate*(45)*. To avoid excessive BOD load on the aeration basins, the elutriate was discharged with the plant effluent to the ocean. It is possible for elutriation to be justified both technically and economically. However, it must be evaluated on the basis of *total* costs and not merely on the single fact that it reduces the costs of chemicals to condition the sludge for dewatering.

There have been reports that activated sludge or a mixture of primary and activated sludges cannot be digested to produce solids readily dewaterable without elutriation. There are, however, hundreds of plants operating in Europe and the USA which are digesting activated sludges and dewatering the solids on sand beds or with mechanical devices and which do not practice elutriation. It is generally conceded that activated sludge does not benefit from anaerobic digestion as much as does primary sludge, and that for activated sludge more conditioning chemicals will be required to obtain proper dewatering. Elutriation may have a beneficial effect regarding some of the polymers now used for sludge conditioning, since some of these polymers would be affected by the high concentration of soluble organic matter that elutriation "washes out."

There are some plants in which elutriation performs a proper function, both technically and economically*(82)*. However, no published information can be found on the complete and total cost evaluation of handling the digested sludge in this manner. In some cases, no "extra" costs are readily apparent, since at present a plant is probably oversized for the wastewater load it is receiving.

To summarize: the original intent of elutriation as developed by Genter—to reduce the very high alkalinity of digested sludge liquor and thus reduce the required dosages of inorganic conditioning chemicals—appears technically sound. It does reduce the quantity of chemicals needed for conditioning, but at the expense of having all the pollutants in the digested sludge liquor in diluted form in the elutriate, together with unsettleable fines. On this basis, it does not appear that elutriation should be considered for general application in the design of new plants. It should be used only under properly designed conditions where effective operation is assured.

7.4 AEROBIC DIGESTER SUPERNATANTS

In some cases, supernatant is not produced from aerobic digestion because the digester contents are kept completely mixed and the digested sludge is hauled away by a tank truck periodically. This is possible at small plants. In other cases, the air to the aerobic digester is shut off and the sludge allowed to thicken before waste activated sludge is added and supernatant is removed and recycled to the activated sludge process. The thickened sludge can be drawn off at intervals to sludge drying beds. Some plants use two-stage aerobic digestion. In these plants, the first stage is completely mixed and the supernatant is produced in the second stage only.

Ahlberg and Boyko*(83)* have analyzed supernatants from seven activated sludge plants employing aerobic digestion located in Ontario, Canada. Three of the plants were conventional activated sludge plants, three used contact-stabilization, and one used extended aeration. Three of the plants had single-stage digestion and four had two-stage digestion. The characteristics of the digester supernatants for the various plants are summarized in Table 4. Ahlberg and Boyko noted that the supernatant flow was generally about 1 percent of the wastewater treatment plant flow.

TABLE 4. CHARACTERISTICS OF AEROBIC DIGESTER SUPERNATANTS (MG/L)

Parameter	Overall Average	Range of Various Plant Averages	Range of Data
pH	7.0	6-8	6-8.0
BOD	500	10-1,700	5-6,000
Filtered BOD	50	5-200	3-300
COD	2,500	200-8,000	24-20,000
SS	3,500	45-12,000	10-40,000
Kjeldahl N	200	10-400	3-1,300
Total P	100	20-250	2-1,000
Soluble P	25	2.5-65	0.5-120
Nitrates	300	200-500	—

The data in Table 4 were obtained from relatively small plants: the largest was 1.85 mgd. Many of these were package-type plants. It was noted that the hydraulic detention times in the digesters were between 15 and 60 days. Studies made under controlled conditions indicate that about 10 to 15 days' detention is sufficient to produce the optimum settleability of the solids for liquid temperatures of 60° to 70° F. Longer times are needed when temperatures drop to 50° F and below. Also, when primary sludge is digested the time should be increased to 20 to 30 days. Many of the digesters shown in Table 4 had very low dissolved oxygen levels—below 0.5 mg/l. This, of course, inhibited nitrification. The higher values of BOD and COD are undoubtedly caused by poor settling of the solids.

The supernatant from a properly operated aerobic digester should have relatively low BOD, since any carbonaceous matter that results from the lysing of microorganisms would be immediately assimilated and oxidized by the living organisms. The remaining organic matter from lysed organisms will be very stable and only very slowly biodegradable. The phosphorus present in the sludge will be dissolved and in the form of orthophosphates that can be chemically precipitated in the digester with alum or iron salts. Nitrates normally will be high since ammonia should be zero.

Drier*(84)* reported some detailed aerobic digestion data obtained at the University of Wisconsin Sanitary Engineering Laboratory. Using mixed primary and activated sludge, the following average data and criteria were obtained:

1. Volatile solids were reduced about 40 percent.
2. The hydraulic detention time was 10 days, with a temperature varying from 60° to 68° F.
3. The solids loading was 0.2 lb/cu ft/day of volatiles.
4. The alkalinity of the liquor dropped because it was used by the nitrification process and because of the stripping of CO_2 by aeration. Adjustment of the pH to between 7 to 8 was desirable.
5. The supernatant, after 1 hour settling had a BOD of less than 100 mg/l and a COD of about 500 mg/l.
6. Nitrification was quite sensitive to temperature at the lower detention times.

Drier also presented some data from well operated full-scale plants that confirmed the above results. It is thus apparent that the package-type plants that were studied by Ahlberg and Boyko, some at liquid temperatures near freezing, were not being operated under optimum conditions.

8. SLUDGE CONDITIONING

In this report, conditioning encompasses those processes which involve biological, chemical, or physical (or combinations of these) treatment to make the separation of water from sludge easier. Also, it should be kept in mind that certain conditioning processes do more than merely increase the dewaterability of sludge; they may also alter the sludge chemically, disinfect it, destroy odors, and may even accomplish a certain amount of destruction of the sludge mass by liquidation or oxidation in some processes.

8.1 CHEMICAL CONDITIONING

Chemical conditioning is a method used to break down the thixotropic and lyophilic and colloidal-gelatinous nature of sewage sludges which makes it difficult to separate the water from the solids. By adding certain chemical flocculants, the "bound" water can be separated from the solids with much less effort and cost. The inorganic chemicals used for such conditioning are alum, ferrous sulfate and ferric chloride, and lime. Alum is used primarily to agglomerate the fine floc of an activated sludge to aid thickening. Ferric sulfate is not used much because of the difficulty of getting it into solution in cold water. Ferrous sulfate is generally used with lime. The most widely used inorganic conditioner is a combination of ferric chloride and lime. The pH is raised to 10.5 to 11.5, and good conditioning is obtained. The high pH causes the death of many pathogenic organisms*(58)*, and would be expected to result in the inactivation of many viruses*(57)*. The precipitated ferric hydroxide is aided in conditioning the sludge by the precipitation of calcium carbonate from the calcium alkalinity in the water and the CO_2, thus adding weight to aid in thickening light sludges.

A great many of the new organic polyelectrolytes, especially of the cationic type, are effective flocculants and conditioners. Their use typically adds less than 1 percent to the dry solids, which can be important in economic considerations for sizing an incinerator. In the large primary plant at Kansas City, Missouri, it was found that the optimum conditioning of raw sludge at the least cost for disposal by incineration was obtained by using a cationic and an anionic polymer in series ahead of vacuum filters*(85)*.

There have been a few instances in which operators changed from the use of ferric chloride and lime conditioning to polymers and found, because of the septic nature of their sludge, that the odors in the vacuum filter room increased markedly. Apparently, the lime treatment, at high pH, prevented any H_2S from evolving, and also the lime tied up some of the odorous organic volatiles*(86)*.

If raw (undigested) sludge is conditioned with chemicals, the liquid that is removed during filtration, pressing, or centrifugation has the same soluble BOD or COD as the plant effluent. The amount of suspended solids may be either fairly low or quite high, depending on the quality of the conditioning and the method used in extracting the water. Centrates will, in general, have higher suspended solids than filtrates. Because there is a high concentration of fine or colloid-type solids, the return of the liquid to the head processes may not permit solids recapture in the treatment plant. Solids recapture may require adding a coagulation chemical, especially in a primary plant.

Sometimes chemical treatment of raw sewage may eliminate the need for conditioning the resulting sludge before dewatering. For example, if raw sewage is to be treated with lime, then, depending on the alkalinity and magnesium content of the water, a coagulant such as alum, an iron salt, or a polymer may be needed. At a pH above 11.0, good coagulation of the suspended solids and settling are frequently obtained with lime alone. Such treatment in most cases produces a fairly dense and easily dewaterable sludge, prevents any odors from developing, and produces a high kill of pathogenic organisms and inactivation of most viruses. A large proportion of the phosphorus is also precipitated. This sludge can be dewatered, usually on a vacuum filter or in a centrifuge, without any further conditioning*(88)(89)*, though the addition of a polymer might be of benefit in some cases.

The ease with which the various types of polymers can be fed has made them popular for sludge conditioning. Frequently they are more effective in increasing solids capture in vacuum filters and centrifuges than inorganic chemicals. They are used extensively with centrifuges.

An indication of the polymer to use for filtration can be obtained by tests in the laboratory. The exact type and dosage may be different from that determined in laboratory tests, however, since polymer effectiveness is influenced by such items as exact point of addition, intensity of mixing, and variations in chemical characteristics of the sludge liquor. There is no good laboratory test for determining optimum chemical dosage for centrifuges*(89)*.

8.1.1 Use of Filter Aids

Many sludges that do not dewater readily without a large amount of conditioning chemicals can be dewatered easily on vacuum filters by adding a "filter aid" such as diatomite, fly ash from coal-fired power plants, or sludge incinerator ash. The production of fly ash from coal-fired plants is tremendous. It has been estimated that if all secondary wastewater treatment plant sludges produced in 1970 were dewatered using such fly ash as an aid, it would only use up about one-third of the total fly ash production. Such fly ash consists principally of silica and alumina, with varying amounts of iron oxides and carbon.

Laboratory studies made on dewatering undigested activated sludge by vacuum filtration, using fly ash as an aid, produced a cake having 40 percent dry solids (including the ash); while without ash the solids were only 25 percent. The ash in the dry cake was about 70 percent—an increase from 33 percent*(90)(91)*. The additional removal of moisture provided sufficient calorific value for self-sustaining incineration of the cake. The ash removed an appreciable amount of COD from the filtrate, reducing it from 90 to 20 mg/l. Also, the phosphates, as PO_4, were reduced from 15 mg/l to practically zero. The filtrate was alkaline with a pH of 8.5 to 9.0. Thus, the use of fly ash on fresh waste activated sludge reduced the release of organic and inorganic nutrients to the filtrate.

Studies have recently been made by the EPA laboratory in Cincinnati*(92)* on the use of sludge incinerator ash for sludge dewatering. This has been practiced at several installations in Germany, using one to five parts of ash for each part of sludge solids. The dewatering is done using vacuum filters or filter presses. There are presently at least two full scale installations of this type in the USA. It should be much more economical to condition sludge with incinerator ash, which would be produced at the treatment plant site, than to haul in fly ash (other things being equal). At Indianapolis, Indiana, 418,000 lb (dry basis) of a mixture of activated and primary sludge are daily conditioned with from 0.25 to 0.50 lb of sludge incinerator ash per pound of sludge prior to vacuum filtration. This has permitted Indianapolis to increase the filter output by a factor of 5, decrease the cake moisture by 22 percent, greatly improve cake release, and drastically cut chemical requirements*(93)*. Incinerator ash is also being successfully used at the 22-mgd trickling filter plant of Cedar Rapids, Iowa, to condition digested sludge for pressure filtration. Although power plant ash was found to be superior to sludge incinerator ash for conditioning, the difference was not sufficient to justify fly ash transportation cost. Recycling of the ash through the incinerator, as would occur in normal operation, did not seem to degrade the ability of the ash to improve sludge dewatering*(94)*.

Light and watery sludge, such as activated sludge alone and alum sludge, can be dewatered (after some chemical conditioning) on a vacuum filter if a filter aid such as diatomite is used as a precoat. Filter presses with such precoating have recently been used for alum sludges, and cakes of 30 to 50 percent solids can be obtained. Of course, a large amount of diatomite is required, which is an appreciable operating expense. The filtrate has a turbidity of about 5 Jtu. The sludge applied to the filter had a concentration of less than 1 percent solids, and the feed rate was 4 to 5 gal./sq ft/hr. The precoat costs average about $2/1,000 gal. of sludge. If the sludge production averages about 1 percent of the liquid treated, then this would amount to about 2 cents per 1,000 gal. of wastewater or about $40 per ton of dry sludge solids processed. Prethickening of a 1 percent sludge to, say, 5 percent by use of a disk centrifuge would be most worthwhile before such a sludge is dewatered on a vacuum filter or a filter press. This is the system proposed for dewatering alum sludge at the Passaic Valley Water Commission water treatment plant*(95)*.

An alum sludge dewatering facility is now in operation at the Atlanta, Georgia, water treatment plant *(96)*. The alum sludge is gravity thickened and conditioned with lime to a pH of about 11. Filter presses operating at about 200 psi are precoated with diatomite and then the conditioned sludge (about 5 percent solids) is pumped into the presses. The filter cake has 40 to 50 percent solids, and the filtrate has less than 10 mg/l of the suspended solids. Alum sludges can be produced at wastewater treatment plants where tertiary treatment is practiced to reduce the suspended solids in the final effluent and to remove phosphorus. Such sludges would have the general characteristics of water treatment alum sludges.

The benefits of using a filter aid must be carefully weighed against the disadvantages. In addition to aiding filtration, bulk dry solids are being added which, of course, makes the sludge drier. If the sludge is incinerated, heat must be supplied to raise these solids to the sludge incineration temperature. Larger dewatering and solids handling equipment is required to handle recycled ash or other filter aids. These factors can affect the cost-effectiveness of total sludge treatment significantly.

8.2 HEAT CONDITIONING

It should be emphasized that this process is not comparable to the so-called "wet air oxidation" process (discussed in Section 10.2), since the end results are entirely different.

It is generally acknowledged that heat treatment of sludges, especially those containing a large percentage of organic matter, will greatly improve their dewaterability. Wastewater sludge can be classified as being to a large degree a colloidal-gel system, and heating allows entrapped water to escape the gel structure. Some have referred to this as heat syneresis*(97)(98)*. Such heat treatment of sewage sludge was first introduced in England in the 1930's.

Basically, this process involves heating partially thickened sludge in a closed reactor to a temperature of 350° to 400° F at a pressure of about 200 to 250 psi, and holding it under these conditions for about 30 minutes. The general system, with required appurtenances, is shown in Fig. 1.

In a modification of the heat treatment process, some air is injected into the heat exchanger and reactor. One reported advantage of this technique is that the conditioned sludge may not emit unpleasant odors. However, the greater production of organic acids and CO_2 depresses the pH to about 4.5 to 5.0, compared to the process without any air where the pH of the liquor is 5.0 to 6.0*(100)*.

Starting in 1968 and continuing to date (1973), some basic studies have been made in England of the heat conditioning process and all its ramifications. Several papers have reported the results of these studies *(99, 100, 101)*. They have originated from university staff studies, investigations made by the Water Pollution Control Laboratory in England, and from operators of actual pilot and full-scale plants. Though the process is being considered seriously in the USA, little basic research has been reported on important aspects such as liquor treatment or recycle and liquor composition in US literature.

It would appear that additional technical and economic consideration is needed regarding the removal of various pollutants in the sludge liquor as a result of the heat treatment. The so-called "cooking" of the organic sludge causes hydrolysis of the carbohydrates, lipids (fats), and proteins. The lipids hydrolyze to various soluble organic acids; some of the carbohydrates break down to simple sugars, while a portion are converted to insoluble polysaccharides and cellulosic compounds. The proteins form amino acids, ammonia, and some carbon dioxide*(99)*.

Some recent studies at the Stevenage Laboratory in England have shown that anywhere from 35 to 60 percent of the suspended solids in the sludge are solubilized by the heat treatment, the higher value being for waste activated sludge. This, of course, reduces the volatiles in the remaining suspended solids. For raw sludge, 24 to 40 percent of the solids was solubilized; for digested sludge, about 15 to 50 percent was solubilized, depending on whether the sludge was from a primary plant or was a mixture of primary and secondary. The remaining settleable solids after treatment will thicken by gravity to 4 to 12 percent solids. On vacuum filtration of the thickened sludge, a cake having 30 to 45 percent solids can be obtained.

Most of the solubilized organic matter appeared in the decant liquor after heat treatment and in the filtrate or centrate when the sludge was dewatered. The studies were both with and without injection of air into the reactor, which resulted in no outstanding differences in the degree of solubilization or total reduction of COD in the sludge*(100)*. The heat treatment

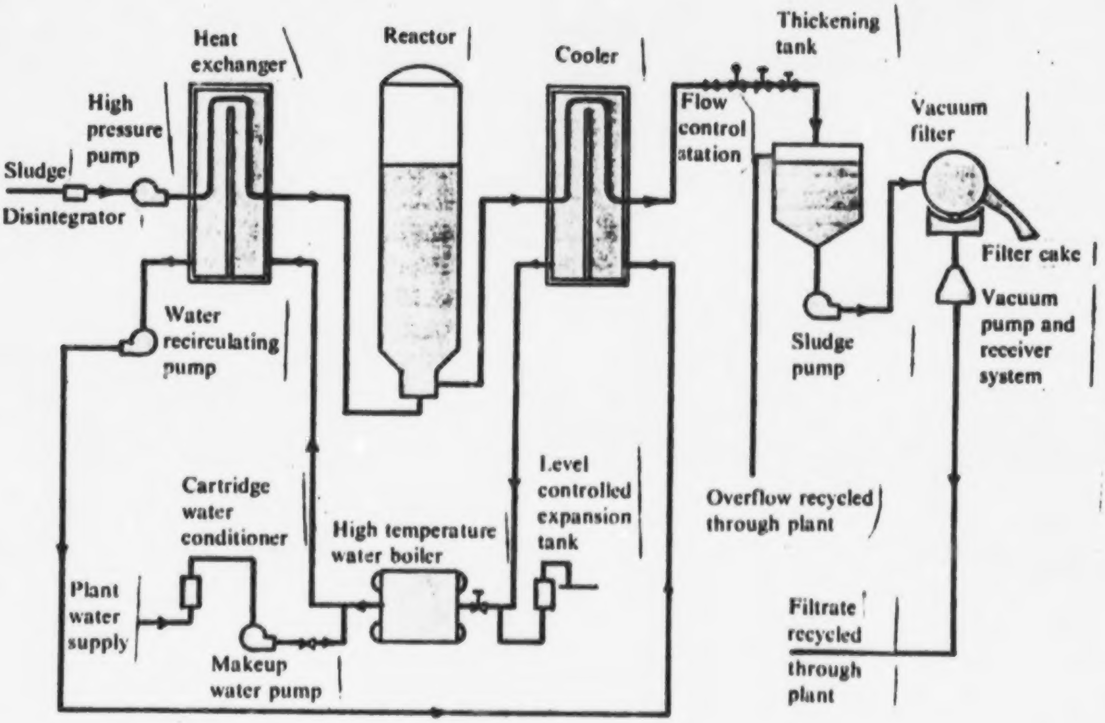
Heat exchanger
Reactor
Cooler
Thickening tank
High pressure pump
Sludge
Disintegrator
Flow control station
Vacuum filter
Filter cake
Vacuum pump and receiver system
Water recirculating pump
Sludge pump
Cartridge water conditioner
High temperature water boiler
Level controlled expansion tank
Overflow recycled through plant
Plant water supply
Makeup water pump
Filtrate recycled through plant

FIG. 1. TYPICAL SLUDGE HEAT CONDITIONING SYSTEM

system that injects a small amount of air into the reactor is not indicated to achieve appreciable oxidation of the organic matter at the temperatures used in this process; about 5 percent of the COD is reportedly removed by the oxidation.

The specific characteristics of the liquor after heat treatment of a mixture of primary and waste activated sludge are: BOD_5 = 3,000 to 10,000 mg/l; BOD_{20} = 5,000 to 15,000 mg/l; COD = 10,000 to 25,000 mg/l; ammonia = 500 to 700 mg/l; and phosphorus as P = 150 to 200 mg/l*(99)(100)*. About 10 to 30 percent of the COD is not biodegradable, at least not in a 30-day test period. Though some of the studies in which the above data were obtained were made in laboratory autoclaves, it was verified that continuous pilot plant studies gave essentially similar results. In one study in England*(102)* where such liquor was recycled to the head end of a 1.0-mgd plant, there was an overall increase in BOD of over 30 percent, expressed as a load (pounds per day) applied to the wastewater treatment processes. The removal of the high concentrations of BOD, COD if necessary, ammonia, and phosphorus would increase total plant costs significantly. The BOD_5 could be removed to a high degree by separate biological treatment of the liquor*(101)*. The nonsettleable suspended solids in the liquor can be anywhere from 1,000 to 3,000 mg/l. Some of these solids could, of course, be removed during filtration or centrifugation, but most of them are colloidal in nature and require biological or chemical flocculation for removal. The total volume of the liquor, including the decantate and the filtrate (or centrate), for an activated sludge plant, will amount to about 0.75 to 1.5 percent of the wastewater flow. It would appear that this sludge conditioning process generates a higher concentration of pollutants in the sludge liquor or liquid sidestreams than well operated anaerobic digestion*(103)*. As with other sidestreams, the problem of removing such pollutants from this liquor, to avoid degrading the final effluent (whether by direct treatment or recycling to the main treatment plant), requires careful consideration and evaluation in the design.

Only if pollutant loads are expressed in terms that indicate the increased cost of additional oxygen required, larger basin capacity, and more chemical or carbon usage can the *total* cost of any sludge processing system be correctly evaluated.

The removal of the high concentration of nonbiodegradable COD by use of activated carbon or ozone oxidation, if required, can be expensive. Some reports have stated that pollutants such as BOD and ammonia in the liquor can be readily handled by the main treatment plant, since such liquors can be stored and fed into the plant when the regular load is relatively low, such as at night. In designing a treatment plant, the quantity of any pollutant that must be removed is calculated typically in pounds per day. Usually, the *daily* loading will determine the size of an aeration basin, oxygen required, chemicals used, etc. This applies to a biological treatment process, a chemical coagulation process, or an activated carbon adsorption process.

A recent study was reported in the *Journal of the Institute of Water Pollution Control* (Gt. Brit.)*(104)* which adds considerably to our knowledge of the character and treatability of the heat treatment sludge liquor. The studies were requested by the London Metropolitan Water Board, because a treatment plant on the Thames River was planning to use heat conditioning in processing their sludge before dewatering with filter presses. The Thames Conservancy District required that the heat treatment liquor be treated separately, including adsorption on activated carbon of the COD, before its discharge. The reasons given were that too little was as yet known about the exact composition of the soluble organic matter in the liquor to permit its recycle to the main activated sludge treatment plant and eventual discharge into the Thames, which was used as a source of water supply downstream. There was, they stated, the possible formation of "unnatural" organic compounds, and it was the nonbiodegradable portion that gave them concern. It had been noted that chlorination of some of these diluted liquors gave rise to taste and odor problem water supplies.

Briefly, the pilot plant study consisted of an extended aeration plant and filtration followed by activated carbon columns. The raw liquor had a BOD of about 10,000 mg/l, a COD of 17,000 mg/l, and an ammonia concentration of 700 mg/l. After treatment, the final effluent had a COD of 52 mg/l on the average and the ammonia content was 130 mg/l, which was considered suitable for discharge into the Thames River. To carry out the treatment, the raw liquor was first diluted 5:1 with treated sewage and then aerated for 4 days, which reduced the COD of the diluted mixture to about 330 mg/l. The MLSS was about 5,000 mg/l in the extended aeration plant. Since further aeration did not accomplish any additional reduction in COD, it was calculated that 2,000 mg/l of the raw liquor COD was nonbiodegradable. The carbon adsorbed about 500 g of COD per kilogram of activated carbon. The carbon regenerated satisfactorily in a high temperature furnace.

The total cost, including amortization and operation and maintenance, was about $4.75 per 1,000 gal. (US) of liquor treated. This was appreciably less than distillation, which was the other alternative considered, and was not regarded as an especially large addition to the total cost of the wastewater treatment plant. If this liquor is 1 percent of raw wastewater flow, which is a typical volume, the cost per 1,000 gal. of wastewater treated would be almost 5 cents. This figure, of course, does not include the heat treatment plant and associated costs.

Field experiences that are reported in the literature regarding sludge heat treatment are scarce.

Continual formation of hard calcium sulfate scale on the heat exchanger in these units can be a serious problem in certain hard water areas. Normal cleaning of the heat exchanger surface is provided for; however, where the water has a high concentration of permanent hardness in the form of calcium sulfate, a serious problem results because of the inverse solubility of calcium sulfate with respect to temperature. For instance, $CaSO_4$ solubility in pure water is about 1,700 mg/l at 212° F, which is about the temperature of the sludge during heat treatment. It thus appears that frequent acid cleaning or some preventive measure must be considered if this process is used in hard water areas. However, as indicated previously, documented data regarding such operational problems are not readily available.

Where the sewage has a relatively high concentration of chlorides, such as may occur from infiltration of sea water, stainless steel heat exchangers could corrode rapidly and special materials may be needed. This occurred at an installation in Florida.

In England, two relatively small plants (about 3 mgd and 5 mgd) use heat treatment for the sludge produced by primary plus trickling filter treatment *(105)*. A filter press is used to dewater the conditioned sludge. The liquor resulting from the heat conditioning of the sludge is diluted with some sewage and treated separately on plastic media filters. The plant has been in operation for 2 years and the paper reports some operational and mechanical problems. However, it appears that most have been resolved and the authors (plant manager and manufacturer's representative) feel that they have a workable plant. The problems encountered were: scaling of heat exchanger surfaces, flotation of solids in the decant (thickener) tank following the heat reactor, furnace problems, odors, and various mechanical failures. Total costs are estimated to average $40 per ton of dry solids (based on direct conversion of English monetary units to US dollars). This does not include cost of disposal.

A recent (1973) pilot study *(119)* on dewatering digested primary sludge produced at the Los Angeles County Sanitation District Treatment Plant showed a total cost of $22.10 per ton for a 300-ton/day facility using vacuum filters after heat conditioning. Vaccum filters plus polymers gave a cost of $12.70 per ton.

There is a general report on the heat treatment installation for the sludge produced at the activated sludge treatment plant at Kalamazoo, Michigan*(106)*. The plant treats domestic wastewater and the wastewaters from seven paper mills in the area. The facilities are designed to handle about 100 tons of dry solids per day. The waste solids consist of 77 percent waste activated sludge and 23 percent raw primary sludge. The reported total costs for heat conditioning, dewatering, and incineration are about $30 per ton of dry solids. Chemical treatment was estimated to cost $10 per ton more. No detailed data are given relating to treatment of the liquor produced by the heat conditioning process. However, the solids capture by the vacuum filters is given as 87 percent, which left about 12,500 mg/l of suspended solids in the filtrate.

At Kalamazoo, a major operational problem reported related to the sludge grinders ahead of the heat treatment unit. This was due largely to the presence of grit in the sludge and an unusual load of industrial rags and pieces of plastic. Plans are underway to provide more effective removal of these materials. Also, a new type of macerator will be tried out in place of one of the grinders. The heat exchanger tubes are cleaned with dilute nitric acid once every 30 days; it is an 8-hr task.

8.3 FREEZING

A detailed study to evaluate conditioning and dewatering of sewage sludge by freezing was sponsored by EPA and carried out by the Milwaukee, Wisconsin, Sewerage Commission*(121)*. The initial conclusion was that the freeze-thaw process has technical merit. However, the final conclusion was that the total cost of the process was greater than existing chemical conditioning processes. One disadvantage appeared to be that it was essentially a batch process. The tests were made on activated sludge having solids concentrations of 1.1 to 5.3 percent. The filtrate suspended solids varied from 100 to 1,000 mg/l, the higher values being obtained from the initially thicker sludges. Storage of the sludge before freezing increased the phosphorus and COD concentration of the filtrate; PO_4 was about 150 to 200 mg/l and COD was 3,500 to 4,000 mg/l. Storage of the sludge after thawing also increased the PO_4 and COD in the filtrate.

Freezing and thawing have been studied at the Stevenage Laboratory in England on a laboratory scale*(107)*. The process was first put to practical use by the Fylde Water Board in England for dewatering alum sludge from a water treatment plant*(108)*. The total costs for this process amounted to about $40 per ton of dry solids. This is for handling sludge having 6 percent solids. They used an artificial freeze-thaw system, involving considerable equipment.

The testing at Stevenage was on activated sludge, raw sewage sludge, alum sludge, and other metal hydroxide sludges. In all instances, except for the alum sludge, the filterability of the sludge on slight stirring, subsequent to thawing, deteriorated. With all the other sludges, any agitation seemed to cause a breakup of the floc. The only way a sludge could be handled after the freeze-thaw step without agitation would be to dewater it in place, thus avoiding the need for pumping or transferring it. This could be done in open drying beds for alum sludge from water treatment plants*(109)*.

The investigators at Stevenage concluded that this process was not suited for organic sludges unless a chemical conditioner was also used, and this would make the process too costly.

A study was made at Ely, Minnesota, to provide basic information for proper design of facilities for dewatering aluminum hydroxide sludges by natural freezing. This technique offers economy for conditioning sludges in cold climates*(110)*.

9. SLUDGE DEWATERING AND SIDESTREAMS PRODUCED

All the various treatment processes sludges are subjected to, such as thickening, stabilization, conditioning, are largely directed towards facilitating the removal of entrained water from the solids. This "dewatering" is accomplished so that the solids can be more economically and more readily disposed of in an environmentally acceptable and cost-effective manner.

The chemical and physical characteristics of the sidestreams that result from sludge dewatering are described in this section. As has been discussed in previous parts of this report, the treatment processes preceding dewatering can have a very important effect on the quantity and quality of these sidestreams.

9.1 SAND BEDS

The most common method of municipal wastewater sludge dewatering is on sand beds. Although sand beds are particularly suitable for small installations, they are used at treatment plants of all sizes and in widely varying geographical areas. Many industrial sludges and water treatment plant sludges are also dewatered on sand beds.

Dewatering on sand beds is by drainage and evaporation. The proportion removed by drainage may vary from 20 to 85 percent. Normally, most of the drainage is accomplished in the first 2 days on the bed; evaporation is the principal effect thereafter. After a few days, the sludge cake shrinks horizontally, producing cracks at the surface which expose additional sludge surface area and enhance the drainage as well. The liquid draining from the sludge is often returned to the treatment plant. Though its volume is small, if the sludge being dried has been digested the drainage contains a high concentration of soluble organic matter, ammonium compounds or nitrates, and phosphates. After one or more months of dewatering, the sludge is removed by a hand shovel or by a mechanical scraper. Only light weight equipment can be used because heavy wheel loads will damage the underdrain system.

The important parameters affecting sand bed design and use are:

> *Climatic conditions.* The amount and intensity of precipitation, percentage of sunshine, air temperature, relative humidity, and wind velocity can affect sand bed design. Temperature is very important; in the Midwest, dewatering rates in summer are about three times as great as in winter. Many plant operators store sludge in digesters during the winter and apply it to beds only in the warmer

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months. Alternatively, more favorable conditions are created at plants where the beds are covered and artificially heated.

Depth of sludge layer. The depth of sludge applied affects the drainage rate (depth should not exceed 8 to 10 in.).

Sludge characteristics. Sludges containing grit dry fairly rapidly; those containing grease more slowly; primary sludge dries faster than secondary sludge; more completely digested sludge dries and cracks relatively fast. It is important that wastewater sludge be well digested, or stabilized chemically or by other means, for optimum drying and to preclude serious odor problems. In anaerobically digested sludge, entrained gases tend to float the sludge solids, leaving a layer of relatively clear liquid that readily drains through the sand. The more water removed by drainage, the less to be removed by evaporation. The overall result is reduced drying time.

Underdrain system. A sludge drying bed must have a drainage system set on an impervious layer of clay or other material. On top of this layer perforated tile should be placed in gravel with collectors so that the liquid can be conducted to a point of treatment.

Drying beds are inexpensive and simple to operate. Their disadvantages are the area required, potential nuisance problems, susceptibility to adverse weather conditions, and the requirement that sludge be well-digested or conditioned before dewatering*(112)*.

The advantages of enclosed drying beds are: reduced area requirements, protection from rain and cold, control of odors and insects, and improved appearance. The disadvantages are the construction and maintenance costs, and the problems regarding the use of any mechanical equipment in a relatively small enclosure. Good ventilation is essential to promote evaporation. In warmer climates, covered beds with sides left open have been effective. This keeps rain from delaying the drying.

The following publications should be referred to for design details on sand beds: *Sludge Dewatering*, WPCF Manual of Practice No. 20, and *Sewage Treatment Plant Design*, WPCF Manual of Practice No. 8. In determining the area for sludge dewatering beds, consideration should be given to climatic conditions and the character and volume of the sludge. At 40° north latitude (St. Louis, Missouri), digested sludge from domestic wastewater requires from 1.00 to 2.25 sq ft per capita in open beds, and somewhat less in covered beds or in southern latitudes. The applied sludge should be well distributed across the drying bed. Since the sludge may be quite viscous and cannot distribute itself well by gravity, the use of multiple discharge pipes is encouraged. Each pipe should terminate at least 12 in. above the bed surface. Splash plates should be provided at the pipe ends to promote even distribution.

Open sludge drying beds in the USA have loadings of 5.5 to 35 lb/sq ft/year. For covered beds, the loadings can be near the higher figure*(113)* (these figures are on a dry solids basis).

After the dried sludge is removed by hand or machine, the drying beds require maintenance. Small sludge particles and weeds should be removed from the sand surface. Periodically, the bed should be disked and the top layer of sand replaced. Usually, resanding is advisable when 50 percent of the original sand depth is lost. The resurfacing of sludge beds is perhaps the major expense in sludge bed maintenance, but there are other factors that should be considered.

Underdrains occasionally become clogged and have to be cleaned. Valves or sluice gates that control the flow of sludge to the beds must be kept water-tight to prevent wet sludge from leaking onto the beds during dry periods. Provision for drainage of lines should be made. Lines with sludge in them should not be shut off until they are flushed out. The partitions between beds should be so tight that the sludge will not flow from one compartment to another, especially if the sand surface is taken down too low. The outer walls or banks around the beds also should be water-tight. If earth beds are used, grass and other vegetation on them should be kept cut.

Sand beds are the most common method of drying sludge, but little has been written about the quality of the resulting filtrate, although this sidestream is frequently returned to the treatment plant. Laboratory studies by Jeffery and Morgan*(114)* in which digested sludge was applied to a 6-in.-thick sand bed indicated that a clear, dark amber liquid was produced with a COD of 300 to 400 mg/l and a 5-day BOD of less than 66 mg/l. The sand removed the suspended solids very effectively. Kjeldahl nitrogen was high, with the long term BOD of over 2,000 mg/l, indicating the typically high original content of ammonia in the anaerobically digested sludge liquor.

As with other sludge dewatering methods, the quality of the filtrate will depend largely on the method used for sludge conditioning, as well as type of sludge; however, sand beds are primarily used for digested sludge. In any case, the filtrate should be returned to the treatment plant and steps taken to handle the additional pollutional load. Of course, since sludge is normally applied to sand beds intermittently, the flow of filtrate will not be continuous. Also, in dry climates there can be appreciable evaporation. Open beds may have diluted filtrates due to rains.

Reportedly, "wedge-wire" drying beds have been used in England with great success*(115)*. These consist of a perforated metal sheet laid on top of conventional drying bed media. Support water is first added to the drying bed to prevent clogging of the media when sludge is added. As the sludge is applied, and as it forms its own filtering layer, the support water is slowly removed. This procedure prevents solids from breaking through the wedge wires and plugging the drying bed. Advantages claimed for wedge-wire beds include: (1) no clogging of the media, (2) constant and rapid drainage, (3) increased bed capacity because higher loadings are possible, (4) easy bed maintenance, (5) easier dried sludge removal, (6) less susceptibility to adverse weather, and (7) difficult to dewater sludges can be dried. Application of this method for use in sludge drying beds has just begun in this country (1972).

9.2 VACUUM FILTRATION

The rotary drum type of vacuum filter has been widely used for sludge dewatering. Basically, there are two types: the stainless steel coil filter and the belt filter, which uses a belt of fabric (usually synthetic) as the filtering medium. The chemical and physical character of the filtrate is largely dependent on the sludge conditioning process used. Vacuum filters will, as a rule, capture a much higher proportion of suspended solids and produce a drier cake than centrifuges.

It is difficult to characterize the filtrate from vacuum filters because of the many variables that affect filtrate quality. These variables include sludge type, degree and method of conditioning, the type of filter media, the amount of vacuum applied, and the sludge application rates. Wherever possible, filter leaf tests should be made to determine cake and filtrate character.

All types of municipal wastewater sludges—raw, digested, primary, activated, trickling filter, and mixtures—can be dewatered by vacuum filtration. The benefit of thickening sludge before filtration has been discussed (Section 6). In general, it has been observed that sludge filtration rates (pounds per square foot per hour) increase as solids input concentration increases. This is because the hydraulic loading that is possible per unit of filter area (gallons per square foot per hour) is generally constant with constant cake thickness. Input solids concentration should be no greater than about 10 percent; at a greater value, chemical conditioning and sludge distribution on the filter drum are hampered.

Since vacuum filters, except in the largest plants, may only be operated for, say, 8 hours a day and maybe 5 or 6 days a week, except in plants having digesters the thickened sludge must be stored during periods when the vacuum filters are not operating. This is done by installing tanks of sufficient capacity between the thickening operation and the vacuum filters. To prevent septicity and to keep the solids from settling, such tanks are aerated, using submerged, perforated pipes, with compressed air. Digesters can, in most cases, provide the required storage, especially if a two stage system is used. Heat conditioning systems have a sludge thickening tank after the reactor which serves also as a storage tank. Since the sludge is sterile, septicity is suppressed.

The above indicated storage facilities may also be needed when centrifuges or filter presses are used for dewatering.

Conditioning prior to filtration is undoubtedly the most important single factor in the operation of any well-designed vacuum filter installation. Lime, ferric chloride, ferrous sulfate, aluminum chloride, and various polyelectrolytes (polymers) have been used sucessfully as conditioning chemicals. Although several years ago (1964) it was estimated that at least 90 percent of the filters then operating used ferric chloride and lime, there is a recent trend towards use of polymers. The advantages cited for polymers compared to inorganic flocculants are:

Significantly smaller requirements for chemical handling equipment and space

Much less incinerator ash produced

Lower heat requirements to heat added chemicals

Greater filter yield in many cases

Improved safety and cleanliness.

To convert from inorganic chemical feed to polymer feed is simple, since existing equipment can be used. Polymeric flocculants have shown no corrosiveness or toxic effects and leave an easily cleaned filter medium and filter drum; however, they do not stabilize, disinfect, or control odors. The use of ferric chloride and lime at a pH of about 11 suppresses odors. If only polymers are used in conditioning, undigested raw sludges cannot be disposed of on the land or in landfills, since they are not stabilized. Typical inorganic flocculant dosages are 400 to 450 lb/ton of dry solids, while typical polymer dosages are less than 20 lb/ton. These figures are for the sludges which are more difficult to dewater.

The solids content in the dewatered cake will be 15 to 20 percent for activated sludge, 25 to 30 percent for raw primary sludges, and 20 to 30 percent for well digested sludges. The filtrate from vacuum filtering, as far as suspended solids and BOD are concerned, is almost entirely dependent on the type of conditioning used. Filtrate flow is normally about 0.5 to 1.0 percent of the plant flow, depending on the prethickening of the sludge. The BOD and suspended solids will usually be removed by the secondary treatment if they are recycled back to the head end of the plant. The ammonia content of the filtrate will be comparable to that of the liquid sludge and will be equal to that of the supernatant for digested sludges. The soluble phosphorus present in digested sludges will be precipitated and removed in the sludge cake, if the sludge is conditioned with lime, an iron salt, or a combination of both.

Malina and DeFilippo*(116)* noted that in the filtrates from vacuum filters suspended solids can range from 100 to 20,000 mg/l, depending on the variables mentioned above. Daily variation at a plant can also be considerable. Five samples collected on 5 consecutive days from a plant dewatering digested sludge ranged in suspended solids from 1,300 mg/l to 7,120 mg/l. Total nitrogen varied from 248 to 9,820 mg/l. Variation in BOD was less—from 300 to 370 mg/l.

In addition to the filter itself, a vacuum filtering system requires a vacuum pump with silencer, a vacuum receiver to separate air from filtrate, a filtrate pump, blowers, chemical conditioning equipment, and sludge feed pumps. A normal design would incorporate:

Separate chemical conditioning tanks to provide flash and slow mix. The tanks should be open to permit observation. Sludge and additives should be mixed to produce the best flow at minimum chemical dosage. Conditioning tanks should be adjacent to the filter and have flume discharges over the lip of the filter pan to broadly distribute the treated sludge. Filtering sludge as soon as possible after chemical conditioning is desirable.

Sludge and chemical dilution facilities. Adequate water lines should be provided to dilute sludge and/or chemical flocculants to optimum solids concentrations, if necessary.

Variable speed filter pan agitator drives. The stability of sludges and their need for agitation in the pan vary, so flexibility in the agitation speed is very desirable.

Delivery of a uniform sludge feed.

Effective filter media cleaning facilities.

In the choice of construction materials, consideration should be given to the corrosive properties of the conditioned sludge. If the sludge is to be conditioned by the use of the iron salts alone or if an acid sludge is to be dewatered, stainless steel, rubber covered construction, or a suitable plastic should be selected. If the conditioned sludge is expected to be alkaline, mild steel construction, perhaps with suitable coatings, would be satisfactory.

Tests have recently been made at the Milwaukee, Wisconsin, wastewater treatment plant on dewatering chemically conditioned activated sludge using a "top-feed," drum-type vacuum filter*(117)*. The thickened sludge was fed from a sealed hopper located near the top of the filter.

The filter drum was not submerged in the sludge as is normally done. Improved yields and cake dryness were obtained compared with filters of conventional design operating in parallel.

If a treatment plant is in existence, then there is no problem in making tests in the laboratory, or even with a pilot filter, to determine the amount and type of conditioning chemicals, maximum possible loading, dryness of cake, filtrate quality, etc. However, for a new treatment plant, the design engineer must establish the general character of the sludge, depending on the type of wastewater and the treatment, using past experience with similar sludges. If the wastewater has industrial wastes which will affect the character of the resulting sludge, the design engineer will have a difficult problem to size the vacuum filters (or any other type of dewatering equipment). Consultation with the equipment manufacturer is important. It may in some cases be necessary to carry out at least some laboratory treatment which simulates that of the proposed plant, to produce some sludge and make dewatering tests on the samples. In such cases, conservative design and provision for additional space are recommended.

Reports on the effect of recycled filtrate on wastewater treatment are almost nonexistent, although it is common practice to return the filtrate, which can contain 1 to 10 percent of the solids applied to the filter. If the solids can be captured by the chemical or biological treatment processes in the plant, no deterioration of plant effluent should result. The quantity of the soluble pollutants will depend on the *upstream* processing of the sludge. In any case, proper design must be provided in the plant to ensure capture of any recycled solids or other pollutants, so that the final effluent is not degraded. In addition, the costs for providing for such capture must be considered part of the sludge processing costs.

9.3 CENTRIFUGATION

The unit generally used for wastewater sludge dewatering is the horizontal solid bowl centrifuge. It operates on a continuous basis and can produce a sludge cake of 15 to 30 percent solids, depending on the type of sludge and the conditioning it receives*(118)*.

The advantages of centrifuges over vacuum filters are less space and, sometimes, lower overall costs. However, in general, the solids capture is not as good as with vacuum filters unless optimum chemical conditioning is used, and then the cake invariably is not as dry. In other words, a dry cake results in less solids capture. The centrate with the suspended solids that have not been removed is typically returned to the head end of the treatment plant.

Centrifuges tend to classify solids; that is, remove the larger, denser solids and leave the finer, lighter colloidal solids in the centrate. These solids are usually very fine and few will settle in, for example, a primary clarifier. If their concentration is excessive, such recycle can cause a buildup of fine solids in the system with eventual discharge in the plant effluent. Of course, if chemical coagulation is employed either in the primary treatment or in the secondary treatment, then such solids will become coagulated and settle out with the other solids in the final clarifier. Biological secondary processes may not capture all such fine solids, and therefore chemical coagulants may be necessary.

Frequently, the activated sludge or the sludge from trickling filters is mixed with the primary sludge and the mixture is dewatered in the solid bowl centrifuge. It is very important that the primary sludge be free of grit, or there will be rapid wearing of the metal lining of the bowl. Even with a standard grit removal facility, it is common to have a hydroclone to degrit primary sludge before it is sent to the centrifuge.

A vertical solid bowl centrifuge, which has recently been extensively tested, is known as the "basket type"*(119)*. It is batch operated, with intermittent removal of the cake, and has a high degree of solids capture. The batch operation can be highly automated. The horizontal bowl and the basket type can be used in series to obtain an excellent solids capture, the basket type unit being the final one. In the basket type, when the unit is stopped, a knife moves down into the vertical bowl to cut the cake, which falls to the open bottom of the machine. Lighter sludges dewatered in this unit produce a cake with 10 to 15 percent solids without chemical conditioning and 20 to 30 percent with chemicals (usually polymers).

Polymers have been extensively used to increase the solids capture in centrifuges; generally, an increase in solids capture results in a wetter cake. The normal solids capture with polymers for primary plus activated sludge is about 85 percent for a cake having 20 to 25 percent solids. In one type of horizontal bowl unit it is possible to add some of the polymer inside the unit after the heavier solids have been removed from the liquid. This increases the solids capture and does not decrease the solids concentration in the final cake to the degree that happens when polymer is added to the total feed*(120)*. Centrifuge manufacturers may have valuable data which would be useful during detailed design of the plant*(121)*.

The effects of returning centrate to the treatment plant vary according to the type of sludge being dewatered. Surprisingly little has been documented regarding effects of returned centrate. Keefer and Kratz*(122)*, in early studies on centrifugation of digested sludge, determined that returning centrate to the plant influent would increase influent BOD by 4.5 percent. Studies were not conducted, however, to determine if continued return would tend to increase the fines in the centrate and thus continually increase the solids returned. It has been found that the return causes recycling of increasing amounts of pollutants because the fine, colloidal solids in the centrate cannot be recoagulated. This is especially true if polymeric flocculants are used for sludge conditioning and an attempt is made to coagulate the fines in the centrate with a polymer. So-called "over-polymerization" can result, so that increases in dosage without changing the polymer cause redispersion of solids*(123)*.

Walters and Ettelt*(124)* believed that centrate from dewatering effluent of the wet air oxidation process should not be recycled unless chemicals were employed to increase solids recovery. They noted that the uncaptured fines, which were extremely slow settling, would present a significant problem in clarification because the solids returned with the centrate would range from 20 to 40 percent of the solids in the feed to the centrifuge.

Perhaps the simplest way to decrease the suspended solids in a centrate is by the addition of chemicals to the sludge before centrifugation. Increases in solids recovery of 15 to 30 percent or more can be achieved by addition of polymers or other chemicals. Reducing the feed rate can also be used to decrease centrate suspended solids. This subject is discussed in some detail by Burd*(1)*.

Recently, studies on centrate from digested sludge were conducted by the County Sanitation Districts of Los Angeles County*(119)*. It was found that the centrate from a solid bowl centrifuge could be further centrifuged in a basket type centrifuge (actually a vertical solid bowl type) after addition of a cationic polymer. This type of centrifuge gave excellent solids capture and produced a dry cake; however, it is a batch unit. The treatment was found to decrease suspended solids, which were about 20,000 mg/l in the centrate from the horizontal solid bowl centrifuge, to about 1,000 mg/l in the centrate of the basket type centrifuge. This combination removed about 97.5 percent of the suspended solids from the digested sludge, which is excellent capture.

Biological treatment of centrate from digested sludge has not been studied to any great extent. It would be expected that such treatment would not be entirely effective because the digested sludge contains some humus materials that are only slowly degradable. The ratio of COD to BOD can be taken as an index of biodegradability. This ratio is about 1.5 for raw wastewater, and a ratio higher than about 5 would indicate a material not readily amenable to biological treatment.

9.4 FILTER PRESSES

The standard filter press, or pressure leaf filter as it is sometime called, has been used for many years in the chemical process industry for dewatering slurries. It consists of "leaves" covered with some type of porous fabric. These leaves or plates form a series of chambers and the sludge is retained between the fabric on both sides of the leaf. These plates are first pushed together and compressed by hydraulic or mechanical pressure exerted on the ends of the series of plates to prevent leakage. Drainage ports are provided in the plates for the liquid to escape. The pressure is imposed by pumping in the sludge which is retained between the filter fabrics. The final pressure can amount to several hundred psi, though usually for wastewater sludge it is about 100 psi*(125)(126)*.

These presses have, in recent years, become highly automated, since they perform basically as a batch operation. After the sludge pumped into the chambers has been retained for a predetermined time at the maximum pressure, the plates are pulled apart and the cake is allowed to fall away from the fabric, normally on a conveyor belt below the press. The automation of the presses has greatly increased their possible application to wastewater sludge dewatering, especially in the USA where labor costs are high. However, to date (1973) no full scale installation of a filter press exists in the USA in a municipal wastewater plant. There is, however, at least one full scale demonstration installation (Cedar Rapids, Iowa), and a similar installation at the Atlanta, Georgia, water treatment plant for dewatering alum sludge.

The principal advantage of the filter press over either the vacuum filter or centrifuge is that it can produce a very dry cake—30 to 50 percent solids—even from sludges that are difficult to dewater. However, to obtain a dry cake and a relatively clear filtrate, chemical conditioning of the sludge is necessary, which always increases substantially the total solids to be handled. Filter presses have been used quite extensively in Europe for wastewater sludge dewatering and are now being tested in the USA. At least three manufacturers in this country now (1973) have filter presses for wastewater sludge dewatering. Some of the best technical information on the performance, theory of operation, capacity rating, and testing of filter presses has appeared in the publications of the Filtration Society of England*(127)(128)*. All types of sludge, varying from raw primary to digested activated, have been dewatered on filter presses with good results and low concentrations of suspended solids in the filtrates. However, proper conditioning is required for efficient operation. Also, possible differences in character of sludges must be considered.

The liquid sidestream from a filter press is generally, for comparable sludges and conditioning, similar to that from a vacuum filter. Because of the higher pressures used and the finer mesh fabrics, the percentage of solids capture in a filter press is generally higher than in a vacuum filter, and thus the suspended solids in the filtrate are fairly low with good sludge conditioning (frequently below 100 mg/l).

9.5 BELT FILTERS

Several designs of this type of equipment, which were originally developed for chemical process sludges and slurries, have been adopted for dewatering of waste activated sludge in Europe. One of these designs was developed in the Netherlands (129) and another in Germany (130). In both cases, the prethickened and conditioned sludge is fed onto the top of a moving horizontal belt. The lower belt is of porous fabric and there is an impervious belt (usually of rubber) on top after the sludge feed point that also moves horizontally on rollers and presses down on the sludge layer, thus squeezing out the water. Solids concentration on the order of 15 to 25 percent can be obtained. The German design is presently being licensed to a USA equipment supplier (131). A somewhat different filter press belt is offered by another USA equipment supplier. This consists of a primary screen onto which the thickened and conditioned sludge is discharged. From this "screen" it moves to a secondary "screen" where there are rollers for pressing out the water from the sludge layer (132). The screens are finely woven synthetic fabrics.

9.5.1 Capillary-Squeeze Belt Filter

A unique type of horizontal belt filter, developed in Europe and used for industrial type slurries and now offered in the USA, depends on the capillary suction action on the water portion of the conditioned sludge to extract the liquid from the sludge layer formed on top of a sponge-like belt*(133)*. The liquid is squeezed out of the "sponge" belt and the cake is further squeezed between steel rollers for additional dewatering. The sludge cake adheres to one of the rollers and is doctored off. Tests show that conditioned waste activated sludge having 0.5 to 1 percent solids can be dewatered to 18 percent solids. The unit is relatively economical and would be especially suited for smaller treatment plants. The solids capture with conditioning is good. EPA tests on this unit are nearing completion (1973).

9.5.2 Gravity-Type Porous Fabric Concentrator

A unit that has been used fairly extensively and was developed in the USA is the so-called dual cell gravity concentrator*(134)(135)*. It has several unique features which produce dewatering of sludge through a synthetic porous fabric by the action of gravity. The first cell accomplishes the removal of the major portion of the water from a thickened sludge, and then the sludge mass is carried over into a second cell where final dewatering is accomplished. The sludge from the second cell is not as dry as is obtained from a vacuum filter or filter press. If further dewatering is desired, the sludge mass is conveyed to a squeezing arrangement consisting of rollers which produce a cake of 20 to 25 percent solids.

9.6 SCREENS

These are devices which are used to remove the larger solids from wastewaters, but which are not strictly dewatering devices; however, they do produce a sidestream which must be recycled to the main treatment plant.

Specially designed self-cleaning metal screening devices are used (and are necessary) ahead of disk (or nozzle) type centrifuge thickeners for waste activated sludge. The liquid coming from such devices must be returned to a primary clarifier, since it contains an appreciable concentration of solids. If primary treatment is not used, then this liquid with the solids must be mixed with the thickened sludge after centrifuging, otherwise the screened out solids will be recycled. However, since the waste liquid amounts to only about 5 percent of the volume of sludge being processed, the thinning out of the thickened sludge is not significant.

A unique automatic mechanical screening device has been recently devloped and used for treating combined wastewater and stormwater flow to remove a large portion of the suspended solids*(135)*. It is called a "centrifugal wastewater concentrator." Reports indicate that the 105-micron stainless steel screen in this device removes about 35 percent of the suspended solids and concentrates them in 10 percent of the total liquid flow. This concentrated stream, which would be the sidestream, is returned to the sanitary sewerage system for further treatment. A modification of this device has been tested out on a raw wastewater, and a full scale installation is being built in California*(137)* for use in place of a primary clarifier.

An unusual use of fairly coarse horizontal and sloping screens, of the vibratory type, is being made at the Hyperion Treatment Plant in Los Angeles to remove the larger solids from digested sludge before it is disposed of. The organic screened out solids are macerated and returned to the main sludge stream, while the inert and hard materials are separated and hauled to a landfill.

Recently, a stationary sloping screen of an unusual hydrodynamic design has been introduced*(138)*. The experience with it is still very limited, but it has application for nonflocculant sludges, such as those from primary clarifiers and trickling filters, and for removing fibrous and discrete particles. The simplicity of design and low cost compared to other systems warrant its being thoroughly tested and considered.

10. FINAL DISPOSAL

This section discusses the various methods currently used to dispose of the sludge to the land, air, or oceans. Fundamental decisions on the environmental acceptability of some of these methods are still being made (1974). In some of the processes, the sludge must be dewatered to a high degree. In others, it is disposed of in liquid form, usually after some thickening. Some processes, such as incineration, may dispose of the organic portion but leave the ash and the liquid (if removed from the sludge before incineration) for further processing and/or disposal. The disposal, by methods other than return or recycle to the treatment plant, of the various liquid sidestreams that can be generated by different processes used in wastewater treatment will be indicated.

10.1 INCINERATION

Since the municipal wastewater solids and sludge (including grit and skimmings) that are generated have a large portion of organic matter, the burning of such sludge should be considered, particularly in larger metropolitan areas. If skimmings are incinerated, a mix tank may be necessary to prevent hot spots and damage to the incinerator. However, an ash remains for final disposal. Whether the combustion is self-supporting depends on the calorific value of the solids and the degree of dewatering that was accomplished. Incinerators are always provided with auxiliary fuel for use when needed--such as during start-ups. Domestic wastewater sludge dewatered preferably to solids content greater than 30 percent will permit self-supporting combustion. Although either may be incinerated, raw sludge is preferable to digested sludge because of its greater calorific value.

Wastewater sludge incineration has been practiced for many years and is being considered in urban areas as sludge volumes increase and as land areas for alternative operations become scarce. Also, the development of greatly improved designs with regard to control of air pollution and possible recovery of heat has increased the use of incineration. However, it is a relatively expensive process in terms of both investment and operating cost. The incineration process must not produce objectionable smoke, odor, or other atmospheric pollutants.

Incineration achieves volume and weight reduction and solids sterilization. The resulting ash will be 15 to 45 percent of the original sludge solids weight (depending on the volatile solids concentration of the feed sludge), and the volume, assuming a 25 percent solids cake as feed, will be about 10 percent. The two most common types of sludge incinerators are the multiple hearth and the fluidized bed. A less common type is the flash drying and burning unit*(140)*.

Incineration of wastewater sludge may be divided conceptually into two major phases: drying and combustion. In drying, the sludge cake is heated to above 212° F, the water is evaporated, and the temperature of the water vapor is increased to that of the incinerator exit gas temperature. For sludge entering with 25 percent dry solids, a typical heat requirement for this drying operation is about 4,000 Btu/lb of dry solids. In some incinerators, drying and burning occur sequentially, while in others both take place in the same chamber. The latter method is characteristic of the fluidized bed unit and the former is characteristic of the multiple hearth unit. In combustion, virtually all of the recoverable heat released may be required to meet the demands of the drying process. Equipment therefore should be designed and operated to achieve maximum practical combustion efficiency. Usually, auxiliary fuel (gas or oil) is provided for startup and for use if the cake should become too wet.

Combustion of the sludge is followed by cooling and scrubbing of the gases to remove fly ash and any unburned particles. Usually, the ash is quenched with plant effluent. In all incinerators there is a possibility of a furnace explosion. Most frequently, explosive conditions are created by allowing unburned fuel and air to accumulate within the furnace, or by feeding highly volatile liquids with a large excess of air. Progressive ignition of sludge and air, as they are introduced into the furnace, is the best insurance against furnace explosions. Proper purging procedures prior to light-off of a cold furnace are essential measures to prevent the possibility of an explosion on startup.

The ash resulting from incinerating wastewater sludge will amount to 15 to 45 percent of the original dry solids by weight and about 10 percent of the volume of, say, a 25 percent sludge cake. The incinerator ash may be disposed of in a landfill and may be an effective filter aid for sludge dewatering. Any slag formation is largely due to excessive temperatures. Available data indicate that, on the average, uncontrolled multiple hearth incinerator gases contain about 0.6 grain of particulate matter per standard cubic foot of dry gas. Uncontrolled fluidized bed incinerator gases contain about 1.0 grain of particulate matter per standard cubic foot. Since particulate emissions standards proposed by the EPA, based on "best control technology," would limit emissions to no more than 0.030 grain per standard cubic foot, 95 to 98 percent of the fly ash must be scrubbed from the flue gas*(141)*. Most systems utilize a variety of wet scrubbers, including venturi, baffle plate, packed tower, and impingement models. However, the emission standard is based on use of a venturi type. Dry cyclones have been used with fluidized bed incinerators followed by a wet scrubber. Scrubber water is a liquid sidestream requiring treatment before disposal, usually by recycling to the main treatment plant. Wet scrubbers also absorb significant amounts of gases which lower the pH.

Most of the ash from the multiple hearth unit falls out of the unit at the bottom into a quench tank. In a fluidized bed unit it is taken out by the dry cyclone. This ash is usually disposed of in a landfill.

Flue gases can produce odors when organic molecules in the sludge are only partially broken down and consumed in the incineration process, thus allowing complex gaseous molecules to escape up the stack. To date, investigation has resulted in a criterion that combustion temperatures must exceed about 1,400° F (about 760° C) to ensure destruction of all odorous components. The thermocouple controls must be set no lower than about 1,600° F to ensure that all parts of the burning chamber are above 1,400° F.

10.1.1 Multiple Hearth Incinerators

The most commonly used incinerator for wastewater sludge is the multiple hearth unit. A vast amount of operating experience exists, and there are at least three manufacturers of such units in the USA. It consists of a circular steel shell with 4 to 12 hearths inside made of refractory material supported on a central shaft that rotates (see Fig. 2).

Dewatered sludge is fed to the upper hearth where drying occurs because of the hot gases coming up from the lower combustion hearths. The combustion occurs on the middle hearths, at temperatures of about 1,500° F. The ash is cooled by the incoming air on the lowest hearth and is then dumped into a quench tank for eventual disposal. The incinerator may be provided with an afterburner to ensure complete combustion of all gaseous organic matter. The gas finally goes to a wet scrubber for removal of particulates.

10.1.2 Fluidized-Bed Incinerators

The first fluidized-bed incinerator for wastewater sludge was installed in 1962. There are now (1973) some 40 units in operation in the USA. The basic design involved a bed of sand, which is fluidized by the upward flow of air, used for combustion. The sludge is fed on top or into the turbulent bed of hot sand and combustion is rapid and complete. There is a gas or oil burner below the sand bed to preheat the incoming air if necessary. The unit operates at several inches of water pressure above atmospheric pressure.

The sludge can be either a solid or a fluid. When the sludge does not have sufficient calorific value to support combustion and evaporate the moisture, supplementary fuel is burned with the sludge. The ability to handle a liquid sludge is one of the principal distinguishing features of the fluidized bed unit compared to the multiple hearth unit which must be fed with "solid" material.

Since the burned gases tend to carry out most of the ash, efficient particulate removal facilities are required. Frequently, a dry cyclone is used ahead of a wet scrubber, which should be no less efficient than the venturi type. In some installations, when handling a sludge of low calorific value, the air blown into the sand bed at the bottom is preheated in a heat exchanger where some of the heat in the exhaust gases is recovered. This increases the overall efficiency of the unit. However, if such preheaters are used ahead of dry cyclones, which is desirable since the cyclone is more efficient when handling a cooler gas, there can be severe abrasion in the heat exchanger from the particles in the fly ash. Such exchangers must be constructed of special stainless steels and be designed for easy maintenance.

The fluidized bed unit is competitive with other types of sludge incinerators and is usually of lower capital cost in smaller sizes, but the operating costs are higher. It has the advantage of being capable of rapid startup; therefore, it can operate with relatively good efficiency for as little as 8 hours at a time. As far as incinerating municipal wastewater sludge is concerned, operating results compare favorably with the multiple hearth furnace.

10.1.3 Drying and Incineration

Another type of incinerator that has been used for many years, but not in great numbers, is the so-called "flash drying ahead of burning" unit. It is somewhat more complex than the other two units described. Briefly, it has a sludge drying stage which is accomplished by dispersing

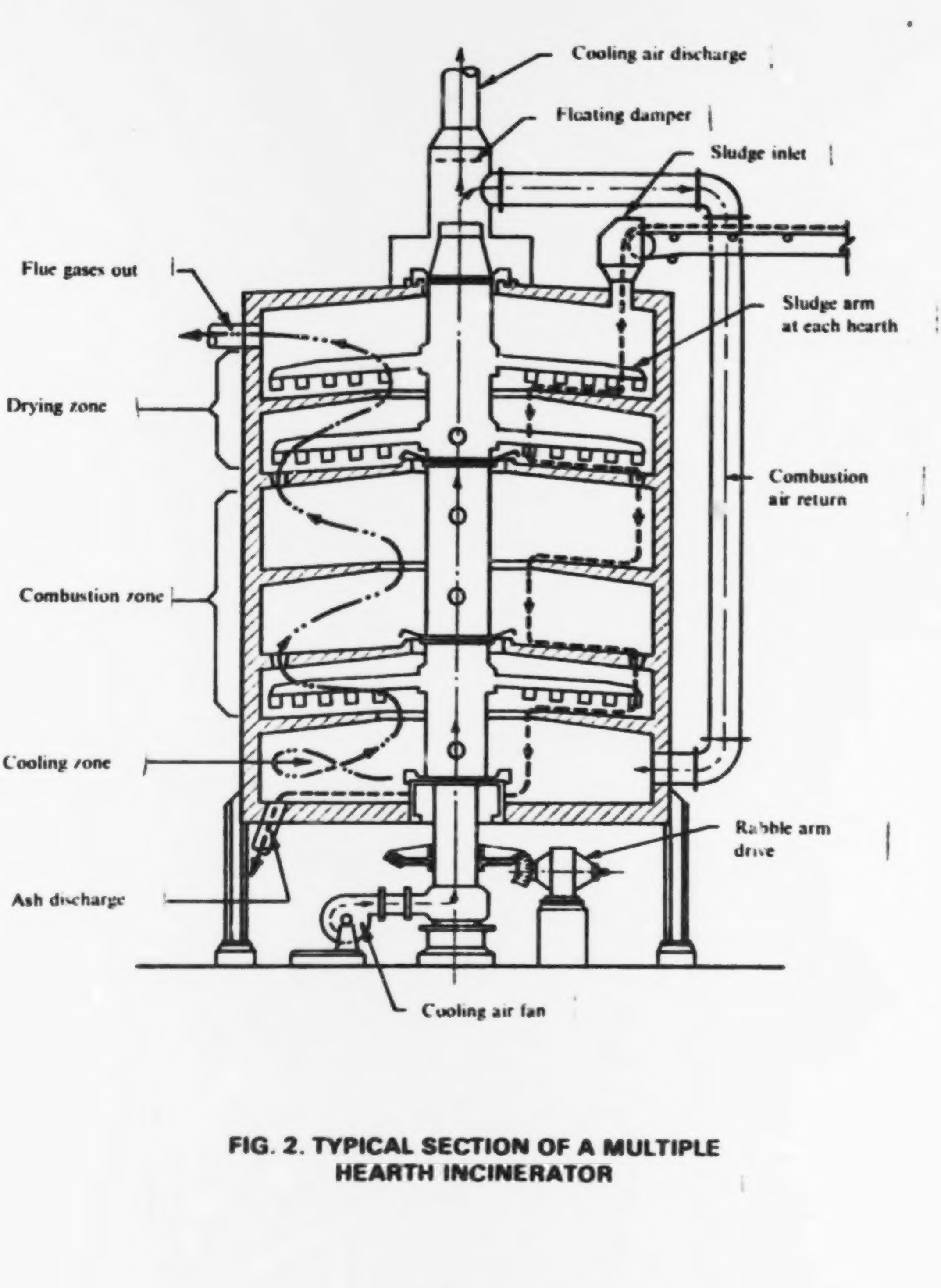
Cooling air discharge
Floating damper
Sludge inlet
Flue gases out
Sludge arm at each hearth
Drying zone
Combustion air return
Combustion zone
Cooling zone
Rabble arm drive
Ash discharge
Cooling air fan

FIG. 2. TYPICAL SECTION OF A MULTIPLE HEARTH INCINERATOR

the solids in the hot gases from the combustion unit and blowing the suspension into a cyclone dryer. The dried sludge is then conveyed to the furnace.

In some instances it is advantageous, for various reasons related to final disposal, to dry the dewatered sludge cake. Of the commercial dryers designed to handle sludge cake, the simple rotary type has been widely used. Drying will sterilize sludge and make it much more suitable for disposal in a landfill, for incineration with municipal refuse and garbage, or for soil conditioning. It has been found that fresh sludge, when dewatered after proper chemical conditioning, can be handled more easily than digested sludge. The latter requires larger units and tends to be slimy and thus interferes with heat transfer from the metal surfaces which are heated with steam or circulating hot oil. The sludge has its moisture content reduced from about 65 to 75 percent to 25 to 35 percent. Any lower moisture content tends to make the sludge "dusty."

10.1.4 Incineration of Sludge With Garbage and Refuse

At some plants, sludge is dried before it is mixed with other solid wastes for incineration. Drying sterilizes the sludge; also, the dried sludge can be mixed better and it does not detract much from the heat value if the heat is recovered. However, it should be kept in mind that, for domestic waste, the ratio of refuse and garbage to wastewater sludge as dry solids will be about 20 to 1. Burning of sludge, even without drying, in a refuse and garbage incinerator is an economical operation if the sludge does not need to be hauled too far. No auxiliary fuel is required, which is frequently the case when sludge is incinerated alone.

10.1.5 Incinerator Scrubber Wash Water

The handling of the sidestream that is generated by use of flue gas scrubbers has not been given much attention in the literature. Little information can be found on the effects of recycling this sidestream to the treatment plant. However, the effects should be slight since most of the organic material should be oxidized during combustion to innocuous end products. This sidestream is, of course, only a small portion of the total produced by the incinerator and associated sludge treatment, and results from the final cleaning of the flue gas.

Tench, *et al.(143)*, summarized analyses of scrubber effluent from two 22-ft-diameter multiple-hearth furnaces at the Sheffield wastewater works in England, where the final effluent is used for scrubbing and is returned to the raw wastewater channel. Suspended solids in the scrubber effluent ranged from 600 to 7,690 mg/l and averaged 1,760 mg/l. COD ranged from 110 to 2,600 mg/l and averaged about 520 mg/l. BOD analyses were on the order of 30 to 80 mg/l. Ammonia nitrogen averaged 90 mg/l and ranged from 30 to 245 mg/l. No influence on plant effluent quality could be detected, since any effects were within the normal range of variations in effluent quality parameters. The ash quench water should be handled in a manner similar to scrubber water.

10.1.6 Incineration of Concentrated Liquids

Liquid sidestreams having high concentrations of soluble organic matter can be incinerated in specially designed incinerators used for liquid wastes of high calorific value. If the sidestream cannot support combustion itself, sufficient auxiliary fuel (gas or oil) can be used to evaporate the water. Such liquid incinerators are built to handle 30 to 500 gph (gallons per hour) of liquid wastes, and can handle waste sidestreams even if they have an appreciable amount of suspended matter. Of course, if the suspended solids are organic in nature, they will be incinerated with the soluble matter. Liquid incinerators are fairly simple in design. They are cylindrical in shape, and a cyclonic action is induced by injecting air in a tangential direction. They are designed for high rate combustion, with waste liquid being sprayed into the combustion chamber as finely dispersed droplets. Another type of liquid incinerator, the fluidized bed incinerator, is widely used for various liquid combustion processes in industry and is well suited for handling liquids having organic compounds of high calorific values in solution and in suspension.

All such incinerators are equipped to accomplish complete combustion, and air pollution by particulates can be controlled with wet scrubbers.

10.2 WET AIR (HIGH-PRESSURE) OXIDATION OF LIQUID SLUDGE

In the wet air oxidation process, organic compounds in the sludge are chemically oxidized in the aqueous phase by dissolved oxygen in a specially designed reactor at temperatures of about 500° to 700° F and pressures from 1,000 to 2,000 psi*(144)*. The degree of oxidation achieved in the process can vary considerably, depending on sludge characteristics, temperature, and detention time. In practice, the process is designed to reduce COD by 70 to 80 percent. Wet air oxidation of sludge produces a sterile, stable product that dewaters and filters readily. The oxidized sludge is thickened and dewatered, usually by settling, vacuum filtration, centrifugation, or a combination of these methods.

Wet air oxidation is especially suited to the treatment of dilute waste liquors and sludges which are difficult to dewater. This is because no preliminary dewatering or drying is required, in marked contrast to incineration. Oxidation of most organic compounds is achieved under high pressure (1,000 to 2,000 psi) at temperatures of 500° to 700° F. The temperatures are relatively low compared to temperatures of 1,500° F or more required for complete conventional incineration at atmospheric pressure. Air pollution is controlled because the oxidation takes place in water and no fly ash, sulfur dioxide, or nitrogen oxides are formed. The remaining liquid is sterile and has a high concentration of inert and organic matter, both in suspension and solution. The COD of the liquid can vary from 10,000 to 20,000 mg/l, depending on the degree of oxidation achieved and the nature of the solids in the raw sludge. This residual carbonaceous matter is present mainly as fatty acids. The organic nitrogen is converted to ammonia, which is not oxidized and remains in solution, since at the pH in the reactor all of it is ionized. The concentration of ammonia can vary from 1,000 to 1,800 mg/l. The BOD in the liquor ranges from 20 to 50 percent of the COD, and reported values of BOD range from 2,000 to 10,000 mg/l. Obviously, this liquid sidestream requires treatment.

The gases from wet oxidation can be odorous, and therefore a catalytic burner is recommended. Also, for the process to be economical, the large amount of energy supplied to compress the air to the required high pressure should be recovered in a gas turbine. A flow diagram of the process is shown in Fig. 3.

Burd concluded in his report that: "The wet air oxidation system is one of the most expensive, overall, of any of the domestic wastewater sludge handling and disposing systems, and requires high quality supervision not normally associated with waste treatment plants"*(1)*.

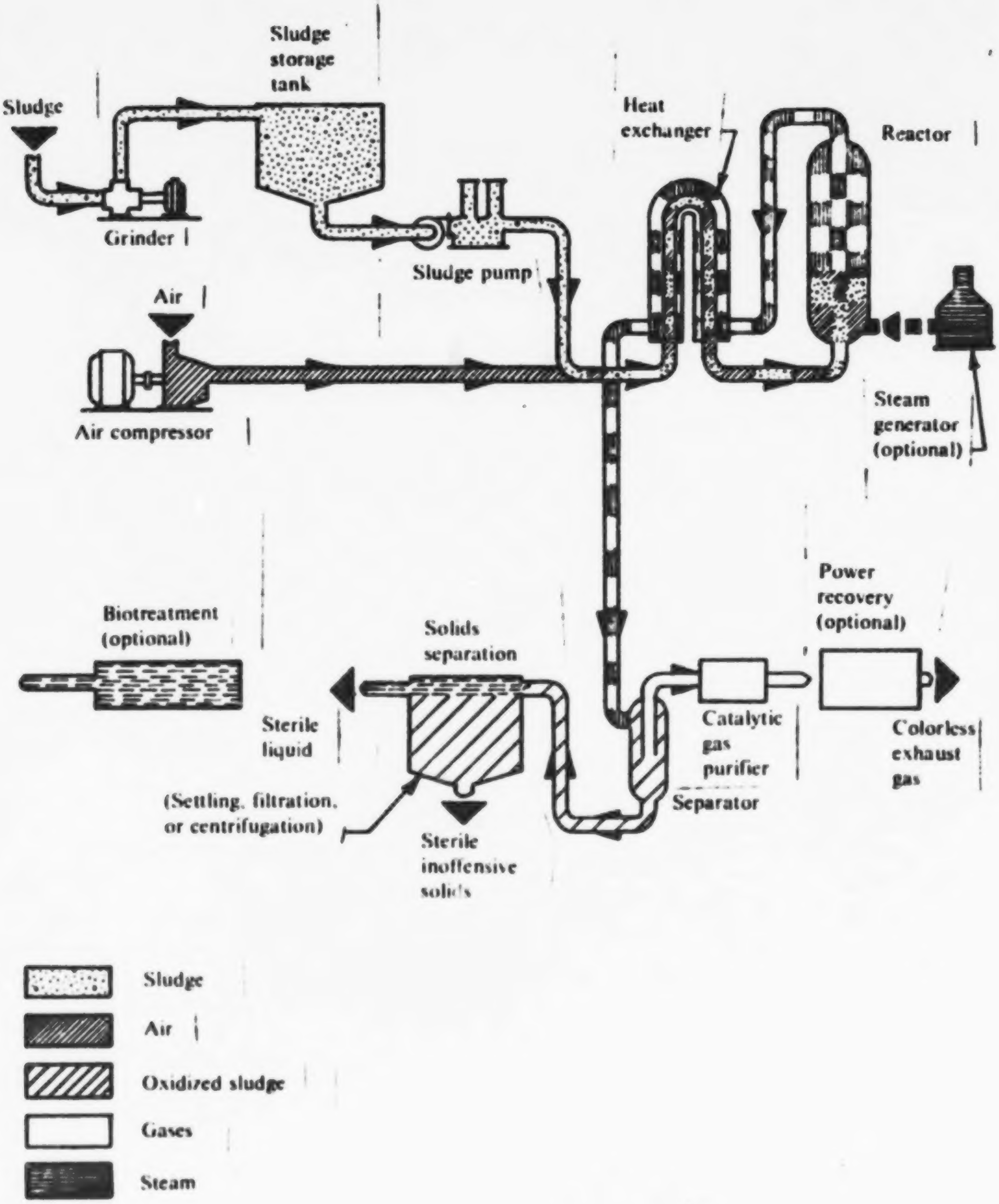
Sludge
Sludge storage tank
Grinder
Sludge pump
Heat exchanger
Reactor
Air
Air compressor
Steam generator (optional)
Biotreatment (optional)
Solids separation
Sterile liquid
(Settling, filtration, or centrifugation)
Sterile inoffensive solids
Separator
Catalytic gas purifier
Power recovery (optional)
Colorless exhaust gas
Sludge
Air
Oxidized sludge
Gases
Steam

FIG. 3. FLOW DIAGRAM FOR CONTINUOUS WET AIR OXIDATION

Erickson and Knopp*(145)* found that the concentrated liquors from settling and filtering wet oxidation sludge could be treated separately by activated sludge without any dilution. Their laboratory studies showed that BOD removal of greater than 90 percent could be achieved at loading rates higher than normally employed for municipal wastewater. BOD decreased from 4,400 mg/l to less than 345 mg/l. COD decreased by about 62 percent, from 8,000 to 2,100 mg/l. The decrease in total nitrogen was slight—from 1,250 to 1,170 mg/l, a decrease of only 6 percent. Total phosphorus decreased from about 30 to 20 mg/l. The liquor volume will amount to 5 to 10 percent of the sludge oxidized, depending on the character and amount of solids in the original sludge.

Apparently, the filtration removed a large portion of the phosphates from the processed sludge. The authors noted that supplemental phosphorus was needed for successful biotreatment. The nonbiodegradable organic matter (COD), fine solids, and ammonia represented additional pollutional load on the plant if they are not removed prior to recycling the liquor to the main plant.

10.3 LAND SPREADING OF SLUDGE

Digested sludge has been spread on agricultural land. Many studies are presently in progress on the various aspects of this method of final disposal*(146, 147, 148)*. Until additional data are available on the composition of heat treated sludge liquor, the disposal of such liquid on agricultural land should not be considered.

The distinction should be made between land application of digested liquid sludge, discussed below, and land application of treated wastewater, which will not be discussed. There are some factors common to both processes, but the principal differences are in the moisture content and solids composition of the applied liquid. When secondary wastewater is applied to the land, the ability of the soil to receive water will ordinarily be the limiting factor. The volume of sludge applied is on the order of 1 percent of the volume of secondary effluent; therefore, hydraulic acceptance will rarely be the limiting factor. The ability of the soil to accept nutrient salts, organic matter, or trace metals will control the rate of application.

Rather than being considered fertilizers, domestic wastewater sludges are considered soil conditioners or soil builders. Soil conditioning provides agglomeration, soil structure stability, pore volume, permeability, air and moisture holding capacity, and the ability to withstand crusting, leaching, and erosion. Although sludges provide some of the needed chemical nutrients, conventional chemical fertilizers will still be required to provide the optimum combination of nutrients for most crops.

Since digestion does not guarantee destruction of all pathogenic organisms, appropriate measures (as will be indicated later on) should be taken to prevent health hazards in applying liquid sludge to land. Other factors of concern are the effects of nitrogen compounds and heavy metals (Cu, Zn, Pb, Cd, Ni, Mn, Mg), especially zinc, copper, and nickel because they can be toxic to plant life*(149)*.

Nuisance-free disposal requires high quality digestion to reduce the pathogen content and prevent putrefaction. Pasteurization has occasionally been required by health authorities in Europe. Lagooning before distribution on the land, although not always essential, does serve many useful purposes such as:

Storage of sludge near the distribution site so that intermittent transport to the site from the plant may be scheduled independently of intermittent distribution

Detention time to permit a more complete die-off of pathogens than may be accomplished by digestion alone

Detention time to permit some nitrogen to escape as nitrogen gas or as ammonia. If not removed before application to land, nitrogen as nitrates may pollute the groundwater, and ammonia may inhibit seed germination.

Distribution may be by furrow irrigation or by sprinkler irrigation. Aesthetically, furrow irrigation is less objectionable than sprinkler irrigation, which is more visible and which may generate a mist of suspended droplets of liquid that can be blown away from the application areas. The sludge may be incorporated deep into the natural soil by burial, deep disking, or rotary tilling. Current research by the Agricultural Research Center of the USDA*(150)*should indicate how helpful deep application may be.

The application to agricultural land of anaerobically digested sludge has been extensively studied and documented. The application of aerobically digested sludge is not well documented, but one may assume that its applicability to agricultural land is roughly equivalent to that of the anaerobic sludge. The organic content of the solids is about the same in the two kinds of sludge. The liquid portion of aerobically digested sludge is quite low in BOD (although it may be high in COD). It also contains nitrates, which have direct fertilizer value. However, if there is danger of groundwater contamination by the sludge liquid, nitrates should be removed at least partially by a denitrifying step prior to application. Comparison of aerobic sludge application with anaerobic sludge will be possible shortly, from results of the practice of both by the Springfield, Illinois, Sanitary District*(151)*.

The sludge accumulating on the ground provides good soil structure and some chemical fertility. A liability is the possible buildup of heavy metals, potentially hazardous to crops or to those who consume the crops. All types of crops appear to respond favorably to application of liquid sludge to land, except when seed germination is inhibited by an excessive ammonium ion concentration *(162)*. At the time of this writing, a technical bulletin is being developed by the Environmental Protection Agency, Office of Water Programs, which will provide guidance on safe sludge application procedures.

10.3.1 Present Practices

Placing sludge on agricultural land has been practiced throughout the world for many years. Some modern, larger-scale operations are described below.

GREAT BRITAIN Digested sludge from 20 to 30 of Britain's 1,200 wastewater treatment plants is distributed to farmland by tank truck. In some cases, sludge is discharged from the truck to a holding pond, then pumped and sprayed to the land. In other cases, the trucks drive over the fields, spraying as they travel*(152)(153)*. Solids content is between 2 and 5 percent. Reportedly, heavy metals concentrations have not been a problem; this may be due to relatively low rates of application (usually not more than 5 tons of dry solids per acre per year), to the lime in the soil which complexes the metals, and effective monitoring program. This method of sludge disposal is reportedly very popular among farmers.

GERMANY In the region between the Rhine and Maas rivers, the Niersverband regional treatment plant has, since 1960, supplied sludge to 820 farms, resulting in increased yields of truck crops, especially beets, and also pasture*(154)*. Wet sludge on grassland has had a favorable lasting effect in reducing evaporation from the soil. Pasteurization before application has recently been provided to comply with health regulations. In Munich, sludge is piped from the treatment plant to neighboring communities and spread on the field by a field railway system.

CHICAGO, ILLINOIS. This operation is the major example in the USA of larger-scale disposal of digested sludge to agricultural land. In contrast to Britain, where the practice is popular with farmers, Chicago has encountered widespread apprehension from farmers, the general public, and state officials about the proposed disposal of sludge to the land. Plans to spread sludge in Kankakee County relatively near Chicago had to be abandoned because of opposition. Plans in various stages of implementation are for sludge to be sent by rail to Arcola, Douglas County, Illinois, and by barge down the Illinois River to Fulton County, Illinois. These rural disposal areas are about 200 miles from Chicago.

For both Douglas and Fulton counties, the Chicago Metropolitan Sanitary District (MSD) proposes eventual replacement of rail or barge transport by pipeline. Meanwhile, the system is to pipe digested sludge from the plant to storage basins, then to barge or haul by tank car. At the disposal area, sludge is unloaded to storage lagoons and aerated to reduce nitrogen content by ammonia stripping. From the lagoons, the sludge is pumped to spray nozzles for spreading.

In Fulton County, the MSD purchased 7,000 acres of land, in contrast to the British practice of spreading on private farms. By purchasing the land, on which MSD pays existing real estate taxes, the district maintains necessary control over management of application rates and multiple purpose land development*(155)*.

Land is prepared by leveling to 5 percent grade or less, and building earth berms to control runoff. Runoff is retained in basins, sampled automatically, discharged to watercourse if quality permits, or returned to the cropland if quality is unsatisfactory. Hedgerows are to be planted around the fields to intercept laterally percolating groundwater which may be overly rich in nutrients.

The barging operation commenced in the summer of 1971 and spraying began in Fulton County in the summer of 1972 over 400 acres. Spraying is expected to be operative over 8 months of the year.

10.3.2 Hygienic Aspects

In Germany and Switzerland, there has been concern about the hygienic aspects of the utilization of wastewater sludge in agriculture. Under unfavorable conditions, viruses, bacteria, parasites, and worm eggs can be disseminated. Health dangers are also present from salmonellae, ascarids, and cattle tapeworm. Pasteurization is recommended and practiced. At the Niersverband regional treatment plant, sludge is pasteurized at 65° C (150° F) for 15 minutes, to comply with health regulations.

Dotson, Dean, and Stern of the EPA laboratory in Cincinnati reported recently*(156)* on studies regarding pasteurizing liquid sludge in a tank truck using injected steam. The hot sludge (160° F) could be cooled by evaporation during spray application to the grassland. They found a thousand-fold reduction in pathogenic and indicator organisms following 60 minutes of exposure of the sludge to a temperature of 160° F.

The airborne transmission of pathogens is an aspect of sprinkler distribution of sludge. There is scant information now (1973) available on this subject. Adams and Spendlove*(157)* report that, as far as 0.8 mile (1.2 km) downwind of a trickling filter, coliforms were detected in aerosol samples. There have recently been other studies on the emission of coliforms from wastewater treatment plants*(158)*. However, there is no evidence that aerosols from any domestic wastewater treatment plant have transmitted disease. Buffer zones should be conservative until more information is available. Also, sprinkler distribution should be restricted to stabilized sludge.

In connection with use of digested sludge on land, studies were conducted on pathogen destruction by digestion by a research group at the University of Illinois. Meyer, *et al.(159)*, studied porcine enterovirus survival in anaerobic digesters. Preliminary results show that a reduction and loss of infectivity can be expected upon suitable exposure of the virus in the digester. Molina, *et al.(160)*, observed the bactericidal properties of digested wastewater sludge --the harmless organisms tended to destroy pathogens. Much work has yet to be done before the mechanism, rates, and necessary conditions for pathogen destruction by digestion are properly understood.

10.3.3 Dried Sludge

Dried sludge, such as "Milorganite" or "Orgro," is available as a fertilizer-soil conditioner. Both activated sludge (Milwaukee) and digested sludge have been dried and processed for use as fertilizer*(161)*. When packaged and dry, it is the most convenient means of supplying sludge to the owner of a small plot of land. However, the economics of producing dried sludge and packaging it are not attractive for new installations. In fact, Milwaukee continues to sell "Milorganite" only because the cost of the installation has been written off. The nutrient content of dried sludge is roughly equivalent to that of the solids portion of liquid sludge. Dried sludge does not contain the nutrients present in the liquid portion of undewatered sludge. For example, a large portion of the nitrogen is in the liquid in the form of ammonia or nitrate and phosphorus is in solution as various phosphates, all of which are removed when sludge is dewatered prior to drying.

10.3.4 Current Studies

The application of sludge to farmland is being studied at the University of Illinois. Conclusions presented in an interim report released in 1971*(162)* are:

> To further reduce pathogen survival in digested sludge, about 2 weeks of lagooning before application to land is practiced to permit pathogen die-off. However, there is considerable doubt whether any significant die-off occurs in such a lagoon. In any case, handling of such sludge has not proved to be a health hazard.
>
> Nitrogen contained in digested liquid sludge is the limiting factor to rates of application. Data indicate that about 2 inches of sludge would satisfy the nitrogen needs of nonleguminous crops without producing excessive nitrate in percolated water. In the interest of higher loading rates, reduction of the nitrogen content of sludge would be desirable.
>
> Heavy metals are ever-present constituents of digested sludge and are usually in the solid phase. After application to soil, they remain in the plow layer with the sludge residue. Solubilization is negligible in soil of neutral or higher pH.

> Plant uptake of Zn, Mn, and Fe has generally been enhanced by sludge application. There is evidence that the uptake is a result not of direct metal addition with the sludge but of induced motility of the metals native to the soil.
>
> Digested sludge has been shown to be a source of nitrogen, phosphorus, and micronutrients. Crop response to the water content has also been observed.
>
> Sludge residue decreases the bulk density of the soil. Grease contained in sludge has not proved to be a problem in clogging soils. Organic carbon has accumulated in sludge treated soils, but has presented no observable problem.
>
> The rate of infiltration of digested sludge is low, regardless of soil type. Thus, on sloping land, special precautions should be taken to control the distribution of sludge applied to the soil surface.
>
> Seed germination is inhibited by freshly digested sludge.
>
> Observations indicate that properly digested sludge will produce no offensive odors after application to soil.

Since 1965, the Springfield, Illinois, Sanitary District has been experimenting with disposal of liquid, anaerobically digested sludge by irrigation of agricultural land. The conclusions they have reached are:

> Although considerable variation in results, because of climatic conditions, may be expected from one year to another, the disposal method is economically feasible.
>
> Sludge should be applied to land utilized for growing crops for animal consumption, rather than to uncropped land.
>
> Soil moisture is a limiting factor in this method of sludge disposal.
>
> Although application of sludge to the land by flooding is possible, this method results in numerous problems, and spray application seems more desirable.
>
> Crops grown on the disposal areas should have a high demand for nitrogen and phosphorus.
>
> Storing of sludge in lagoons for later distribution has not proved practical [a result providing some conflict with the recommendation by Hinesly, *et al.(162)*, cited earlier, indicating that 2 weeks of lagooning were provided to permit pathogen die-off].

Molina, *et al.(163)*, have studied the effect of aeration on liquid digested sludge. Reduction in ammonia-nitrogen content of the digested sludge is brought about within a few days by aeration or by aging in contact with the air. Reduction in ammonia is important, because it evidently inhibits the germination of certain seeds sown on sludge applied to land.

The most widely recommended application rates in the US for cropland are from 10 to 20 tons of dry sludge per acre per year*(164)(165)*.

10.4 LANDFILL DISPOSAL OF DEWATERED AND STABILIZED SLUDGE

It is important to distinguish between two related concepts:

> Dumping of stabilized and dewatered sludge cake on land, generally without cover
>
> Sanitary landfill, involving the controlled and systematic burial of stabilized dewatered sludge beneath a suitable earth cover.

A stable sludge can be the result of biological digestion, treatment with lime to pH of 11, or conditioning by use of heat treatment. Current (1973) studies by the U.S. Department of Agriculture are being conducted to determine the greatest amount of sludge that can be applied to the land for maximum benefit and minimum hazard. This is sludge dewatered to about 22 percent solids. Most of the sludge is applied by burial in trenches 2 ft wide and 2 or 4 ft deep, covered by 1 ft of soil. Other incorporation methods, such as deep disking or rotary tilling, will be tested eventually. A variety of industrial and domestic wastewater sludges is being used in varying amounts. Fruit and shade trees, shrubs, fescue grass, alfalfa, corn, soybeans, and tomatoes are among the crops being tested.

Dumping is the simplest and least imaginative sludge handling operation possible. Dumping, long practiced as a means of final sludge disposal, has apparently been satisfactory when:

> Sufficient land area is available.
>
> The dump site is sufficiently far from populated areas that odor and appearance are not a nuisance and the pathogen content is not a hazard.
>
> Runoff to watercourses is controlled.
>
> Percolation of leachate to groundwater is controlled.

In the past, all four of the above conditions have not always been met. The EPA has a stated policy to convert dumps to well designed and properly managed landfills. Naturally, odors increase in intensity with increased rates of sludge volumes deposited. Odors from incompletely stabilized sludge can be reduced, but not satisfactorily eliminated, by soil cover.

Sanitary landfills require no less area but considerably more operational expense per ton of solids processed than simple dumping, nor can such landfills guarantee elimination of odors from incompletely digested sludge or sludge incompletely stabilized. Landfilling is the most common means of disposal of incinerated sludge ash. Incineration reduces an odorous and pathogenic dewatered sludge cake to odor-free ash with only 3 to 10 percent of the mass of the cake. The corresponding decrease in volume from cake to ash often makes incineration and landfill of ash an attractive alternative to landfill of sludge cake, where available land is scarce or distant.

For the disposal of municipal refuse and garbage, see the sanitary landfill information developed by the Office of Solid Waste Management.

A properly designed and operated sanitary landfill can be made nuisance-free and acceptable from an environmental health standpoint. Studies conducted during the past few years indicate that a considerable potential for groundwater contamination does exist. Most landfills will eventually produce leachate, as well as gases. The quality of leachate depends on the degree of decomposition activity within the landfill. Adequate digestion or chemical stabilization of sludge before disposal to a landfill is essential to avoid poor quality of leachate. The exact required dryness of the sludge cake for landfill disposal depends on the character of the sludge. The cake must be such that, after covering with earth, compaction equipment can be driven over it. To minimize leachate quantity, the landfill operation should be kept an adequate distance above the high groundwater table, and surface runoff from areas tributary to the landfill should be intercepted in drainage ditches to carry it around the landfill. It is possible, and may be necessary, to collect and treat leachate before it reaches a stream or other fresh surface or groundwater supply.

Prevention of rainfall percolation into the landfill also reduces the pollution potential. This can be accomplished by adequate surface slopes in combination with impervious surface ditches, maintenance of the landfill such as filling settlement areas immediately, and the planting of cover crop to consume a large volume of water. The use of a tight cover material will also decrease the rate of rainfall percolation, but adequate vents should be provided for the gases that are produced in the decomposition process.

When a landfill is used for land reclamation, it should be remembered that the new compacted refuse and sludge will tend to settle. Cameron*(166)* developed equations to predict the degree of settlement and the period required for settlement using centrifuged digested sludge. Factors affecting settlement were found to include degradation of volatile solids and initial moisture content.

The EPA Office of Solid Waste Management has cited*(167)* the following as advantages of a sanitary landfill:

> Where land is available, a sanitary landfill is usually the most economical method of solid waste disposal.
>
> The initial investment is low, compared with other disposal methods.
>
> It is a complete or final disposal method, compared to incineration and composting which require additional treatment or disposal operations for residue, quenching water, and unusable materials.
>
> It can be put into operation within a short period of time.
>
> It can receive all types of solid wastes, eliminating the necessity of separate collections.
>
> It is flexible, and increased quantities of solid wastes can be disposed of with little need for additional personnel and equipment.
>
> Submarginal land may be reclaimed for use.

The disadvantages cited include:

> In highly populated areas, suitable land may not be available within economical hauling distance.

Proper sanitary landfill standards must be adhered to daily, or the operation may result in an open dump.

Sanitary landfills located near residential areas can result in public opposition.

A completed landfill will settle and require periodic maintenance.

Special design and construction must be utilized for buildings constructed on completed landfill because of settlement factor.

Methane and other gases produced by decomposition of the wastes may become a hazard or nuisance problem and interfere with the use of the completed landfill.

10.5 OCEAN AND SURFACE WATER DISPOSAL

10.5.1 To Surface Water Other Than Ocean

Disposal of wastewater sludge to navigable waters is regulated by EPA under Section 405 of the Federal Water Pollution Control Act Amendments of 1972.

In the interior of this country, especially in the west, there exist bodies of saline and brackish water that could be used for disposal of concentrated inorganic brine solutions. Since usually the volume of such brine sidestreams is small, pumping or haulage by tank truck or railroad tank car could be feasible. Of course, for coastal cities, disposal of such brines into the ocean may be possible (see Section 10.5.2).

In general, land disposal of brines will not be acceptable due to contamination of the land and groundwater with the salts present in the brines. For example, a sidestream containing an appreciable concentration of ammonium salts could not be disposed of on most land areas, since such salts would eventually be converted to nitrates by bacterial action, and the increase of nitrates in groundwater that might be used for domestic purposes must be considered unacceptable.

10.5.2 Ocean Disposal

At the time this report was prepared (1973), EPA policy on ocean disposal of wastewater sludge was being developed in response to new legislation. Enactment of PL 92-532, the Marine Protection, Research, and Sanctuaries Act of 1972 on October 23, 1972, gave EPA statutory authority to regulate ocean dumping of most materials, including wastewater sludges. Regulations and guidelines for this purpose are now being developed. When available, these regulations and guidelines will establish the EPA policy on ocean disposal of sludges.

10.6 DEEP WELL OR UNDERGROUND INJECTION

Deep well or underground injection may be acceptable for inorganic brine only. There are presently many deep well injection systems in use in the oil fields for brine disposal and in other localities for liquid wastes disposal. Such deep well injection is a highly developed technology and it can, in certain instances, be a relatively simple method for disposal of concentrated sidestreams, especially those containing soluble inorganic matter.

Such underground injection involves comprehensive geologic investigations and field testing to establish that the liquids will not clog the porous formations, are compatible with the water already in the formation, and there is no danger of pollution or encroachment on underground water supplies. A factor to be established is that such injections will not cause earth movement.

Waste streams to be disposed of by underground injection must be free from suspended matter, unless it has been established that the waste is to be placed in an underground cavity, either natural or man-made. Their chemical composition must be such that precipitates will not form on contact with various rock formations and thus cause rapid clogging.

Any system for the disposal of a liquid sidestream by underground injection must be designed by experts in this field, since the technology is specialized and highly developed. The method is used in the oil fields extensively for so-called "secondary recovery" of oil from porous strata by injecting waste brine from oil well operations*(168)*.

10.7 PYROLYSIS OF SLUDGE

Pyrolysis is a process involving the heating of organic matter in the absence of oxygen. The term "destructive distillation" is used when wood is subjected to this treatment to produce methanol. Depending on the nature of the organic matter, the decomposition of sludge by pyrolysis at temperatures varying from 900° F to 1,700° F produces compounds such as: char, tars, various liquids, and gases such as hydrogen, carbon monoxide and dioxide, methane, and ethane.

Most of the studies reported in the literature on pyrolysis have been made on refuse and garbage. The city of San Diego has been conducting such studies for many years*(169)*. Their studies showed that the process, once started, is self-sustaining by using one or more of the end products as a fuel. In general, the volume reduction for such solid wastes is about 50 percent. The char, for instance, has a Btu content similar to that of semianthracite coal. The liquids, or pyroligneous acids, can be used as a base material for various organic compounds. From the tests on dried wastewater sludge they found that the end products were generally similar to those from refuse and garbage.

Extensive studies of pyrolysis of municipal and industrial solid wastes have been conducted by the U.S. Bureau of Mines*(170)*.

Studies at the University of Western Ontario*(171)* were made recently on pyrolyzing vacuum filtered wastewater sludge. Before pyrolysis, the sludge had 85 percent moisture, 47 percent ash, and 32 percent carbon on a dry basis. The tests were conducted in a multiple hearth type furnace fed with an oxygen-deficient gas (about 2 percent oxygen): a temperature of about 1,300° F was maintained. This burned off the volatile gases produced with minimum oxidation of the carbon residue, referred to as the pyrolysate. The carbon pyrolysate was tested to determine its ability to adsorb residual organic material in a treated wastewater effluent. The tests showed that this carbon residue had an adsorptive capacity between that of fly ash and activated carbon. Thus, the possibility of using pyrolyzed sludge as an adsorbent for tertiary treatment of wastewater is indicated.

A study was conducted by Rensselaer Polytechnic Institute on so-called partial combustion, using oxygen deficient air, with true pyrolysis being a limiting case*(172)*. The tests were made in fluidized bed reactors using materials such as ground paper, dried wastewater sludge, and dried leaves. The partial combustion reformed the complex compounds, and generally the end products were not too different from when true pyrolysis occurred, and hydrocarbons predominated when pyrolysis was used. Separation of the mixture of compounds into valuable products is not a simple problem.

At present, as far as is known, no continuous full scale operation using either partial combustion or pyrolysis exists, either for refuse and garbage or for wastewater sludge. However, various tests are in progress. A large scale (5 tons per day) pilot plant operation has been conducted at Mt. Vernon, New York, by the Union Carbide Co. This is a unique combination of pyrolysis and oxidation. To date they have only studied refuse and garbage, but dewatered wastewater sludge cake could be mixed with the refuse.

The Garrett Research and Development Corp. of LaVerne, California, and Hercules, Inc., of Cumberland, Maryland*(173)*, have both described pilot plant studies involving pyrolysis of refuse in which the economic justification rests on recovery of valuable end products from various complex organic materials.

As far as wastewater sludge is concerned, since it must be dewatered to a degree comparable to that required for complete incineration, there does not appear to be any sound economic or technical justification for using pyrolysis unless a useful byproduct can be recovered, such as a char which can be used in place of expensive activated carbon for adsorbing a large portion of the soluble organic matter in clarified wastewater effluent.

10.8 COMPOSTING OF SLUDGE

This process for treating dewatered organic wastewater sludge is related to aerobic digestion. It stabilizes sludge for final disposal. A large portion of the organic matter is oxidized to carbon dioxide, water, nitrates, and phosphates. The process involves the destruction and decomposition of the volatiles in the organic sludge by thermophilic aerobes (organisms whose optimum temperature is 135° to 160° F).

There is an immense amount of literature on composting, especially of municipal refuse and garbage. The method has also been applied to solids originating from vegetable and fruit canning operations and to processing various manures*(174)(175)*. Composting plants for garbage and refuse have not been successful in this country—not for technical reasons, but because financing of such plants was based on obtaining a certain price for the compost, which was not realized. The process offers many attractive features for preparing organic solids for disposal on the land. It is considered a part of the general solids handling and disposal system that is being engineered for the state of Delaware by Hercules*(173)*.

The composting of wastewater sludge, except for one study which will be discussed later, has been done by mixing dewatered fresh or digested sludge with refuse and garbage*(176)(177)*. There are many such installations in Europe. The primary reasons for mixing are that dewatered sludge, averaging 75 percent moisture, is too wet to compost by itself, and the wastewater sludge adds the nitrogen necessary for biological action for the nitrogen deficient refuse.

To maintain aerobic conditions, the composting mass must be sufficiently porous so that air can penetrate it readily. For wastewater sludge, this means a moisture content of about 50 percent. The ratio of carbon to nitrogen and to phosphorus must be in the range required for any aerobic biological oxidation and synthesis. There is usually an excess of nitrogen and phosphorus present in raw wastewater sludge; in any case, there is no deficiency. The moisture content must be maintained at a proper range and, if artificial aeration is applied to a composting mass, as is done in mechanical composters, this air must be monitored and controlled so that the optimum temperature is maintained once the thermophilic organisms have become established. The moisture content cannot be allowed to go too low, since these organisms require moisture for their activity.

After composting, the organic matter resembles slightly moist humus (about 25 to 30 percent moisture), and has an "earthy" consistency and odor. It can be disposed of on the land as a soil conditioner or an innocuous landfill. Since an average temperature of 150° F is maintained for at least 5 days, all pathogenic organisms, including viruses, are killed or inactivated.

In 1967-68, the Bureau of Solid Waste Management of the U.S. Department of Health Education and Welfare supported a research study on the composting of dewatered sewage sludge without mixing it with any other material*(178)*. The sludge studied was a mixture of primary and secondary sludge from the Salt Lake City wastewater treatment plant. The sludge was chemically conditioned and dewatered on a vacuum filter. The tests were made in a 40-cu-ft mechanical composter equipped with a specially designed agitator mechanism. Air was supplied through a porous bottom of the unit under controlled conditions to maintain the proper temperature and amount of moisture. Recycling the final product to the head end of the unit served to maintain the desired moisture concentration in the composter and also seeded the incoming fresh sludge with thermophilic organisms. The composting reduced the original sludge cake volume by about 60 percent and the weight by about 85 percent. The final product had a fertilizer value of cattle manure and was free from viable plant seeds and pathogen indicators. It could be stored outdoors, uncovered, without causing any odors or accumulation of flies or other insects.

When the sludge was conditioned with ferric chloride and lime, its pH was about 11.0. This dropped to 6.5 very rapidly after the sludge entered the composter, because of the large amount of CO_2 generated. When the sludge was conditioned with polymers, the moisture content of the cake was about 50 percent higher; this made operation of the composter somewhat more difficult, and a higher recycle was needed. Otherwise, the end product was practically identical, except that the iron-lime conditioned sludge gave a fine-grained product.

It was of interest that the dry solids were reduced by 30 percent, which means that this portion of the sludge was oxidized. There were no noticeable odors from the composter. The test work did not permit extrapolation so that costs could be estimated for a full scale plant, since the studies showed up several design weaknesses in the equipment. However, rough estimates indicated that such a composter and appurtenances would have a total cost no greater than an anaerobic digester for handling the same amount of dry solids by weight. This assumes that the digested sludge would be vacuum filtered; for composting, the raw sludge must also be vacuum filtered. The operating costs probably would be higher for the composting installation.

One possible problem area in composting, however, is heavy metals. While its is true that composting of sludges appears to reduce metals translocation to crops, care must be taken that the original sludge is of sufficiently high quality. At the time of this writing a Technical bulletin is being developed by the Environmental Protection Agency, Office of Water Programs, which will provide guidance on safe sludge composting procedures.

11. RECLAMATION AND REUSE OF SLUDGES

Methods of processing various sludges so that the whole or portions of them could have a beneficial use would obviously be of considerable significance with regard to ultimate disposal. Therefore, such possibilities should be explored and evaluated.

11.1 ALUM RECOVERY

If chemical coagulation with alum and subsequent settling and/or granular media filtration are used to reduce the suspended solids in a wastewater treatment plant effluent, the resulting sludge will be light and difficult to dewater. Tests should be made using a deep, coarse media filter to determine if the gravity sedimentation step could be omitted. The solids that are accumulated in such a filter are densified and agglomerated so that they can be settled out of the backwash water very readily, and thus the volume of sludge that must be disposed of is greatly reduced.

Studies have been made in the USA and other countries on recovering the alum from this sludge when there is a high percentage of aluminum hydroxide. By acidifying the sludge with commercial grade sulfuric acid to a pH of about 2.5, the aluminum hydroxide will be dissolved and converted to aluminum sulfate (alum). The organic and other solids can be settled out of such a solution; they form a relatively small volume for final disposal after neutralization with lime. The solution with the recovered alum would, of course, be reused. There are several wastewater treatment plants in Tokyo which produce water for various industries. The total capacity of all the plants is 400 mgd. At all these plants, the above described method of alum recovery is used.

This method is economical at the Japanese plants, and also greatly simplifies the waste solids disposal problem*(179)*, but it has the disadvantage that acidification of the sludge will redissolve any precipitated phosphates, iron, and manganese. This can be a serious handicap if phosphorus must be low in the treated effluent. The only phosphorus removed in such a recovery process would be that in solution in the blowdown from the clarifier after acidification. This would also be true of any precipitated iron or manganese. The problem could be controlled by increasing the acid solution blowdown or by wasting some of the alum sludge, but the recovery efficiency would decrease. In either case, more makeup alum would be needed. Also, it may be necessary to add lime to the water being coagulated to provide sufficient alkalinity.

An alum recovery plant treating a low turbidity water supply (capacity 38 mgd) is in operation at Daer, Scotland, and is quite successful and justified economically both from the aspects of saving alum and simplifying sludge disposal*(180)*. A water treatment plant in Warsaw, Poland, also uses the acid recovery system*(181)*.

Another method for recovery of alum from sludge is the alkaline process using lime. This process was originally developed by the Lurgi Co. in Germany. It consists of adding lime to the alum sludge and stirring vigorously at a pH of 10 to 11. With this treatment, about 50 percent of the aluminum is recovered as a calcium aluminate, which can be reused as a coagulant together with fresh alum. The solids residue settles and thickens readily. With this process, the phosphates and any iron and manganese precipitates would not redissolve.

11.2 RECALCINATION OF LIME SLUDGE

If lime is used, with resultant precipitation of calcium carbonate and calcium phosphates, the sludge probably should not be biologically digested, since some of the phosphate will be solubilized as the pH drops to neutral in the digester from generation of CO_2. However, some recent limited studies indicate that digestion is possible, with only partial solubilization of the calcium phosphate*(27)*. Such sludges can be easily dewatered on, say, a vacuum filter and disposed of in landfills or by incineration. The multiple hearth furnace has been adapted to accomplish the dual function of incineration and calcining the precipitated calcium carbonate to CaO. Because of the difference in density of the ash and the CaO, a fairly high degree of separation can be achieved in a dry cyclone, and about 50 percent of the required lime can be recovered. Consideration must be given to the buildup of MgO and various inorganic inert material. Such recovery is practiced at the Lake Tahoe waste treatment plant*(182)*, which has a capacity of 7 mgd. This method would not be economical for small plants.

11.3 HYDROLYSIS OF ORGANIC SLUDGES

Hydrolysis of organic materials has been used to make available otherwise undigestable food ingredients. After hydrolysis, the solubilized material is concentrated to a thick syrup which is referred to as "molasses." (This term is used irrespective of the origin of the syrup, whether it be from wood, soybeans, sorghum, cane, etc.) It has value as an animal feed and currently sells for about 2 to 5 cents per pound.

The simplest method of hydrolysis is by injecting sulfur dioxide gas into a slurry of solids, then heating it to about 135° C under pressure and holding it at this temperature for about 3 hours. Such studies were made using a concentrated activated sludge under sponsorship of the EPA*(183)(184)*. About 50 percent of the sludge is solubilized. The cooled mixture was readily filtered to produce a cake having 40 percent solids and a liquor of light yellow color, having 8 percent by weight of dissolved solids and a pH of 3.0. The liquor was concentrated in an evaporator to 60 percent dissolved solids, which were 18 percent ash and 82 percent organics. The fate of trace elements in the hydrolyzed sludge should be checked before feeding to animals in the human food chain.

12. OTHER TERTIARY AND ADVANCED TREATMENT PROCESSES

12.1 MICROSTRAINING

Microstraining with a rotary drum type strainer has been used for removing suspended solids from final clarifier effluents. The openings in the stainless steel fabric are on the order of 25 microns. The flow through the strainer is due to a differential head of a few inches of water. The screen is continually washed by directing a stream of clean water opposite the direction of flow during the straining operation. This wash water with the suspended solids will amount to about 3 to 5 percent of the flow being treated. Wash water is usually returned to the final or primary clarifier.

Tests of the final clarifier effluent at a wastewater treatment plant in Baltimore showed that the suspended solids were reduced on an average from 20 to 12 mg/l and the BOD from 20 to 10 mg/l*(185)*.

Large scale tests were made at the Chicago Metro Hanover Plant, and it was shown that the microstrainer, under certain hydraulic loadings, could reduce the suspended solids to 5 mg/l if the influent solids loading did not exceed 15 mg/l*(186)*. It was not effective in removal of alum-coagulated solids. There are over 30 microstrainer installations in Great Britain for reducing the suspended solids in final wastewater effluents. However, on an average the strained effluents have suspended solids of about 15 mg/l. Microstrainers are not reported to be effective in removing colloidal solids*(187)*.

12.2 FILTRATION AND ADSORPTION USING GRANULAR MEDIA

Various types of gravity and pressure filters with granular media are used for removing suspended solids of various types and concentrations to reduce them in effluents. The media may be sand; coal on top of sand; coal, sand, and garnet; mixtures of the above (mixed media type); activated carbon on sand; or activated carbon alone. When activated carbon is used, some adsorption of soluble organic compounds is desired and obtained. However, such adsorption must be relatively low, or the carbon would have to be removed frequently either for disposal or regeneration.

In recent years, granular media filters with relatively large granules have been built much deeper than the standard 2- to 3-ft filter used for some 50 years in water treatment plants. Such deep filters, up to 20 ft, with large void volumes, are used to remove concentrations of suspended matter of 100 to 200 mg/l at filtration rates up to 10 gpm/sq ft and higher from wastewater.

The Europeans have used modified designs of granular media filters for many years in wastewater treatment. The so-called upflow filter*(188)* developed in the Netherlands has had wide application and is now available in the USA. The filters are cleaned of the accumulated suspended solids by taking the filter out of service and backwashing it with clean water (filtered effluent usually), at rates which expand and fluidize the bed to about 100 to 125 percent of its original volume. Frequently, air is bubbled up through the filter to produce a violent scrubbing action and clean the granules, and then the water is turned on to remove the loosened dirt.

The backwashing of granular media filters produces a liquid sidestream with a relatively high concentration of suspended solids, varying from 100 to 1,000 mg/l, which may amount to 1 to 5 percent of the water filtered.

The volume of backwash water used varies between about 1.0 to 3.5 percent of the volume of water filtered in studies on filtration of activated sludge plant effluent*(186)*. No correlation with solids loading or removal rates has been observed, but it was found that the ratio of backwash flow to flow treated decreased with the hydraulic loading rate (in gallons per minute per square foot) and with increasing head across the filter. The filtered effluent averaged about 3 mg/l in both BOD and suspended solids. The removal of suspended solids averaged about 70 percent and BOD removal averaged about 90 percent. The backwash water volume amounted to about 2 percent of the wastewater filtered, and had an average BOD of 1,350 mg/l and suspended solids of about 350 mg/l.

The backwash water volume for upflow sand filters treating trickling filter effluent having suspended solids of 30 mg/l and a BOD of 20 mg/l was about 1.25 percent of the volume treated*(189)*. Suspended solids in the wash water were 2,260 mg/l at 1 minute after the start of backwashing; they increased to 6,525 mg/l after 2 minutes; and then decreased to 80 mg/l after 7 minutes.

The backwash water characteristics depend on the type of effluent applied to the filter. For example, wash water from filters treating the effluent from coagulation or other chemical treatment would contain alum, lime, iron salts, polymer, or other chemicals in addition to the pollutant removed.

The backwash water is frequently recycled to the final clarifier; however, storage must be provided since the backwash rate is several times the filtration rate and, unless there is a multiple filter installation, the hydraulic load on a clarifier would be excessive. With storage, the backwash water can be recycled over a period of several hours. The suspended solids must, of course, be kept in suspension by some means of agitation.

In some cases the backwash water may be settled in a separate clarifier, and the overflow can be mixed with the plant effluent. An important characteristic of the solids that are washed off granular media filters is that they are compact, dense, and fast settling even though ahead of the filter they may have been light, small, and flocculant in character. In other words, the filter tends to densify and agglomerate the suspended solids in a wastewater effluent, whether they be organic or inorganic in composition. Thus the disposal of this particular liquid sidestream is usually a relatively simple operation.

Granular activated carbon columns of the downflow type require backwashing usually on a daily basis to remove the accumulated suspended solids and bacterial growths. Though such backwash water usually has a low concentration of suspended solids, it should be returned to a preceding clarifier in the plant. It is now becoming fairly common to use upflow columns to prevent the accumulation of anaerobic biological growths. Also, effluents having some suspended solids can then be treated without clogging the bed*(190)*. Of course, the final effluent would usually require filtration if the suspended solids are to be kept low.

12.3 BRINES AND CONCENTRATED SOLUTIONS

The disposal of brines and other concentrated solutions can usually be facilitated by one of the modern desalination methods. For salt concentrations below 2,000 mg/1, three processes show good potential for desalination: ion exchange, reverse osmosis, and electrodialysis. *Ion exchange* in combination with chemical processes has the dual potential of producing potable water while at the same time concentrating the solids up to 8 percent by weight. It has the disadvantage of contributing solids to the salt disposal problem. *Reverse osmosis* has the advantages of being a nonselective, highly dependable, low operating cost process. It has the disadvantage of discharging large volumes of low concentration brine, from which the pump energy must normally be extracted by a turbine for good power usage economy. *Electrodialysis* has the advantages of being fully commercial, having good power economy, and also having a good concentrating factor for the waste brine. Its main disadvantages are membrane poisoning, polarization, and so-called spalling of the membrane surfaces by chemical scale when improperly operated. These three processes produce large volumes of waste brine containing all of the contaminants removed in rendering the municipal wastewater effluent suitable for reuse. Determination of the costs for ultimate disposal of these waste brines has been studied in detail*(191)(192)*.

In general, waste brine disposal might be accomplished by underground injection, land spreading (with proper consideration for groundwater contamination), or sea discharge by pipeline. Evaporation, either to saturation or dryness, can be used ahead of final disposal. However, in inland areas the cost of brine (or other solution) disposal can be a major factor in renovation of municipal wastewater. Where solar evaporation can be used, the cost can be as low as 5 cents per 1,000 gallons and up to 75 cents per 1,000 gallons. Brine injection into deep wells in Arizona has been estimated to cost about 15 cents per 1,000 gallons; however, in other parts of the country it can vary from 3 to 35 cents per 1,000 gallons.

The disposal costs are highly dependent on climatic and geologic conditions. Some brines, especially those having fairly high concentrations of organics, will undoubtedly require pretreatment before disposal.

12.4 ION-EXCHANGE TREATMENT

A considerable number of studies have been made on the use of ion exchange for removing various nutrients such as nitrates, phosphates, and ammonia from wastewaters. Also, ion exchange could very likely be used to keep down the concentration of various inorganic salts, which are difficult to remove by precipitation, when a wastewater is being recycled or reused. Such treatment might be done on only a portion of the total water being reused. [illegible]

An ion-exchange process that has received considerable study is that of ammonia removal from wastewater effluents. Certain zeolites, including the naturally occurring mineral clinoptilolite, have a high selectivity for the ammonium ion*(193)*. After the column of ion-exchange material is exhausted, it is regenerated with limewater containing sodium chloride to speed up the regeneration. The high pH of the limewater converts the ammonium ion to ammonia gas in solution. The ammonia is allowed to build up to about 500 mg/l during regeneration. The regenerant solution containing the high concentration can be air stripped of the ammonia. The regenerant also could be reacted with waste sulfuric acid and a solution of ammonium sulfate produced which, on evaporation, could be converted to a fertilizer, or perhaps in some places it could be used directly without evaporation. In any case, the disposal of this sidestream can be a problem and can increase the cost of the process significantly. Recently (1972), studies by the Battelle Northwest Laboratory have indicated that, using a high concentration of NaCl in the regenerant solution, electrolysis can be used to produce free chlorine and thus destroy the ammonia by breakpoint chlorination. However, strict control of the pH is required to avoid producing the obnoxious nitrogen trichloride

When demineralization is the purpose of ion exchange, acid resins for removing cations and base resins for removing anions are employed in series. The acid resins exchange H^+ for the cations while the base resins exchange OH^- for the anions. When the exchange capacity of the resins is exhausted, the units must be regenerated by passing an acid through the acid resin columns and a base through the base resin columns. The regeneration step produces sidestreams for the process. Another sidestream is produced when the columns are backwashed to remove particulate matter. Backwashing is necessary every one to five regeneration cycles*(194)*. The practice has been to recycle the backwash waters, which amount to about 4 percent of the product flow.

An ion-exchange process developed by Rohm and Haas Co. and called the "DeSal" process has been shown to be effective in renovating secondary wastewater effluents*(195)*. Good removal of nitrates, phosphates, detergents, etc., is achieved. The anion resin can be regenerated by use of ammonia and then brought back to the bicarbonate form with pressurized carbonated water. Appreciable removal of COD is obtained and organic fouling of the particular resin is not reported to be a problem. The regenerant (sidestream) is, of course, composed of a solution of nitrates, phosphates, etc., which must be disposed of. Unless the plant is near the seacoast or in a desert or a wasteland area, such disposal is a problem.

A "concentrating" process such as ion exchange, as far as pollutants are concerned, is not particularly attractive, since the pollutants originally present in the wastewater are also present in the concentrated sidestream. Ion exchange does have application for removing certain nonpolluting soluble inorganic compounds to keep their concentration below a level desired for, say, reuse of the water.

Regenerant solutions from ion-exchange systems have high concentrations of solubles which present difficult disposal problems. In some cases, the soluble compounds can be precipitated or chemically altered.

12.5 ELECTRODIALYSIS

If a cationic and an anionic membrane are immersed parallel to each other in a three-compartment vessel containing an ionic solution, ions can be induced, by applying an electrical potential, to migrate out of the central compartment into the outer ones, leaving the water in the central compartment with a lower ionic concentration. Cations and anions migrate out of the ionic solution through the anionic and cationic membranes, respectively. This process has been studied in the desalination of sea and brackish waters. It has been shown that the process can be applied to demineralization of secondary wastewater effluent*(196, 197, 198)*. It is most efficient if only a portion of the salts need be removed to keep the concentration within acceptable limits. The capital cost of electrodialysis equipment is relatively high compared to other advanced wastewater treatment processes. The disposal methods for the brine or concentrated solution are similar to those for ion-exchange brines. In general, the electrodialysis unit should be placed at the end of the various wastewater treatment processes where the concentration of organic matter is lowest and the concentration of inorganics the highest. Organics cause membrane fouling.

12.6 REVERSE OSMOSIS

Reverse osmosis has been extensively studied for use in advanced waste treatment and for desalination of water*(199)(200)*. The use of a process that can remove various solubles, especially inorganic types, from wastewater is desirable in some locations to decrease the dissolved solids content of the effluent. Studies on the application of this process to wastewater treatment have been limited to date (1973) largely to bench and pilot plant investigations. It is a process which affords the engineer concerned with wastewater renovation a great deal of latitude both with regard to the quality of the feed supply and the desired effluent quality. It is essentially a membrane process, but the membranes can be designed to remove fine suspended solids in addition to soluble organic and inorganic matter.

Two streams are produced in the process: the product water, or permeate, and the sidestream, or concentrate. Several design variables affect the quality of the concentrate, including treatment before application to the reverse osmosis unit, efficiency of the membrane in rejecting salts, and the percentage of water recovered in the process. Waste treatment before reverse osmosis has included: settling, chemical treatment followed by settling, activated sludge treatment, and activated carbon treatment of activated sludge effluent*(200)(201)*.

Studies have been conducted to determine whether reverse osmosis concentrates can be treated by the activated sludge process to remove organics*(202)*. Two of the studies used chemically flocculated and settled effluent. In one, ferric chloride was used as the flocculant, and in the other alum was used. Both studies found that greater than 90 percent removal of total organic carbon could be obtained.

Reverse osmosis appears to have considerable potential in the wastewater treatment field because of its great flexibility to remove ions of various molecular weights, from NaCl to large protein molecules having molecular weights of several million. This is made possible by "tailoring" the membrane to the particular separation process. Membrane life is the major operating cost, but great advances have been made in recent years to extend this life for various operating conditions.

12.7 DISTILLATION

The investigations that have been carried out and the technology developed by the Office of

Saline Water with regard to distillation of sea and brackish waters might be applied to renovation of wastewaters. Studies indicate that the costs will be less than those of seawater conversion*(203)(204)*. In general, it will be applied to removing solubles from a portion of the treated wastewater stream that is being reused, so when the distilled water is mixed with the main stream the concentration of salts will be within the desired limits for the particular use of the wastewater.

The problem of disposing the sidestream containing the high concentration of solubles may not be simple, depending on the type of solubles removed and the geographic location. It may be necessary to concentrate this sidestream.

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201. *Reverse Osmosis Renovation of Primary Sewage*, EPA Report No. 17040-EFQ-02/71 by Envirogenics Co. (February 1971).

202. *Amenability of Reverse Osmosis Concentrate to Activated Sludge Treatment*, EPA Report No. 17040-EUE-07/71 by Rex Chainbelt Co. (July 1971).

203. *Cost of Purifying Municipal Wastewater by Distillation*, Report No. AWTR-6 of Public Health Service, Dept. of HEW (November 1963).

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APPENDIX

MATERIAL BALANCE ANALYSES

This appendix describes procedures which may be useful in the design of systems for processing sludges and liquid sidestreams in a wastewater treatment plant. Particular emphasis is given to recycling sidestreams within the treatment plant itself.

THE QUANTITATIVE FLOW DIAGRAM

To present all the facets of process performance and interaction needed for computation of required process capacity, it is helpful to use a quantitative flow diagram (QFD). Individual processes are represented by labeled circles or rectangles and flow directions are represented by arrows.

A simple example will serve to show the utility of the QFD for design purposes. For simplicity, consider a three-process plant consisting of: (1) primary clarification, (2) anaerobic digestion of the sludge, and (3) transport and disposal of the digested sludge to agricultural land. Digester supernatant is recycled to the primary clarifiers. It is assumed (though experience indicates it unlikely) that the same percentage of solids will be removed from the supernatant as from the raw waste. The average plant flow is 10 mgd, with an influent suspended solids concentration of 250 mg/l. Of the suspended solids flowing into the clarifier, 60 percent is removed in the sludge, whose solids concentration is 6 percent or 60,000 mg/l. The sludge stream goes to the digester. The digester supernatant volume flow is equal to 10,000 gpd (gallons per day). The supernatant's suspended solids concentration is assumed to be 5,000 mg/l. It is estimated that 25 percent of the solids entering the digester is converted to gas and escapes from the system or is solubilized. It is assumed that volume balance is maintained, which is approximately true, since the loss or gain of liquid volume by evaporation or by biological metabolism is minor.

Therefore, one of the basic relations for any unit or process is the volume balance relation. The other relations are those for mass balance of the pollutants. The volumetric flow of digested sludge to land disposal, for example, is calculated as follows: First, the blank QFD (Fig. A-1a), with the primary clarifier and anaerobic digester, and the six associated flows—influent, effluent, raw sludge, recycled supernatant, removed solids, and digested sludge—is constructed. The heavy lines around digested sludge discharge emphasize that it is the quantity to

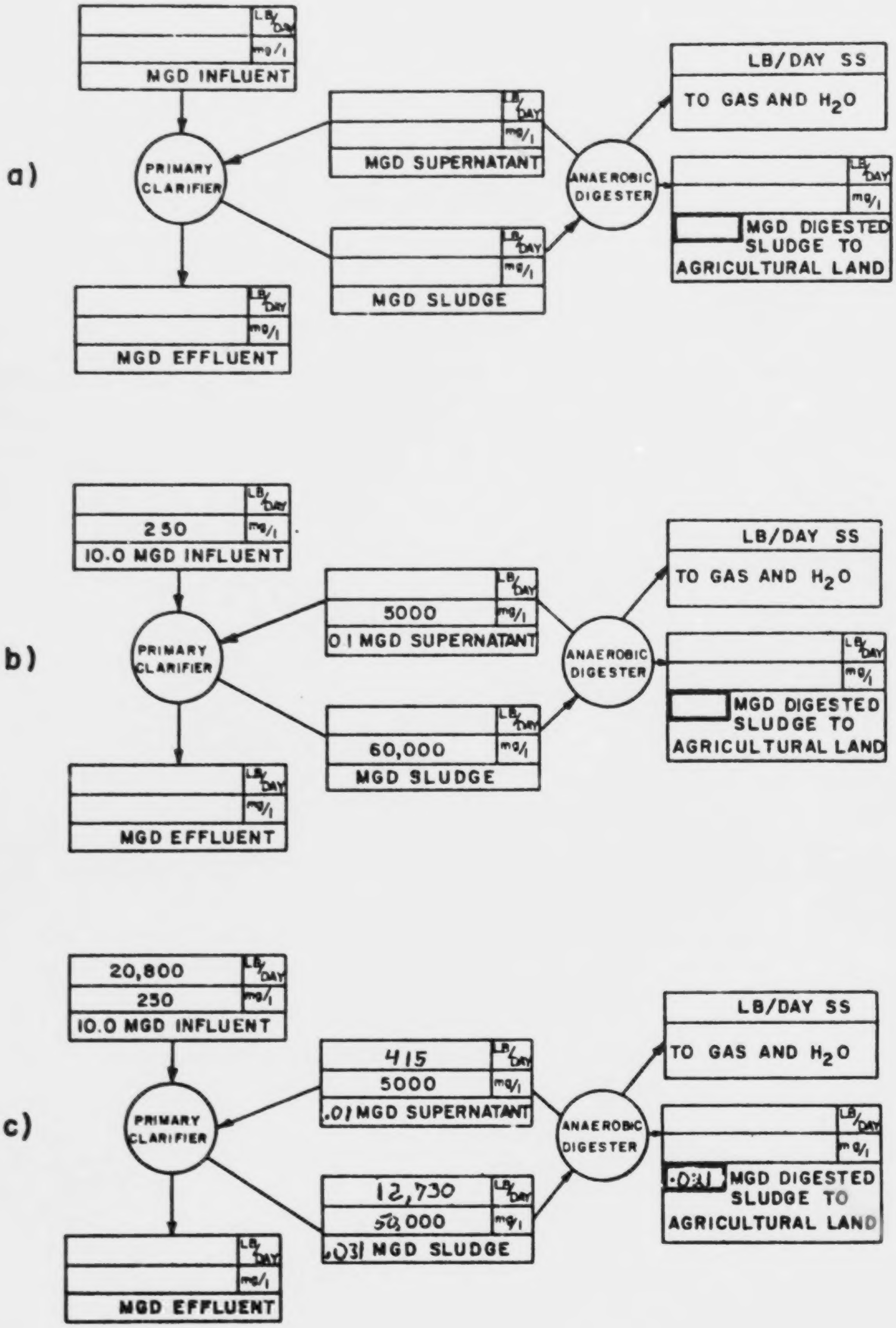

a)
LB/DAY
mg/l
MGD INFLUENT
PRIMARY CLARIFIER
LB/DAY
mg/l
MGD SUPERNATANT
LB/DAY
mg/l
MGD SLUDGE
LB/DAY
mg/l
MGD EFFLUENT
ANAEROBIC DIGESTER
LB/DAY SS
TO GAS AND H2O
LB/DAY
mg/l
MGD DIGESTED SLUDGE TO AGRICULTURAL LAND
b)
LB/DAY
250 mg/l
10.0 MGD INFLUENT
PRIMARY CLARIFIER
LB/DAY
5000 mg/l
.01 MGD SUPERNATANT
LB/DAY
60,000 mg/l
MGD SLUDGE
LB/DAY
mg/l
MGD EFFLUENT
ANAEROBIC DIGESTER
LB/DAY SS
TO GAS AND H2O
LB/DAY
mg/l
MGD DIGESTED SLUDGE TO AGRICULTURAL LAND
c)
20,800 LB/DAY
250 mg/l
10.0 MGD INFLUENT
PRIMARY CLARIFIER
415 LB/DAY
5000 mg/l
.01 MGD SUPERNATANT
12,730 LB/DAY
50,000 mg/l
.031 MGD SLUDGE
LB/DAY
mg/l
MGD EFFLUENT
ANAEROBIC DIGESTER
LB/DAY SS
TO GAS AND H2O
LB/DAY
mg/l
.021 MGD DIGESTED SLUDGE TO AGRICULTURAL LAND

FIG. A-1. DEMONSTRATION OF A QUANTITATIVE FLOW DIAGRAM be determined. All the information given above would then be filled in (Fig. A1-1b): influent flow and suspended solids concentration, supernatant flow and suspended solids concentration, and raw sludge concentration.

The suspended solids loads in pounds per day for influent and supernatant would then be computed from the values for discharge and concentration. Next, all suspended solids loads entering the clarifier would be added: 20,800 pounds per day + 415 pounds per day = 21,215 pounds per day with 60 percent, or 12,730 pounds per day, going to the sludge stream. From this value and the given sludge concentration, the derived volume of the sludge stream is 0.031 mgd. The volumetric discharge of digested sludge is therefore equal to raw sludge discharge minus supernatant discharge, or 0.021 mgd.

The appropriate spaces on the QFD should be completed as computations are made (Fig. A-1c). As soon as the bold-line box is filled in, the problem is solved, although some of the other spaces are still blank.

This simple example serves to emphasize that:

> All aspects of plant operation should be set down together on one diagram.
>
> Although pollutant loads are usually expressed in terms of concentration (mg/l), the relative importance of the various streams is shown most clearly by comparison of mass flow values (lb/day).

It should be noted that:

> Various quantities can be computed by a volume-balance and mass-balance approach: the mass (volume) flow into a process must equal the mass (volume) flow out. The "mass in" includes the mass introduced by all inflows, whether the main plant stream or a recycled sidestream, and includes mass introduced by chemical precipitation or biological synthesis. "Mass out" includes mass removed by the main effluent, sludge, liquid sidestream, off-gassing, or biological synthesis. Because the solids that are volatile and converted to a gas cannot be determined, mass balances around certain processes can only be estimated.
>
> Computations are not always straightforward, but may require a trial and error approach, particularly where recycle streams are involved.
>
> Neither influent volume and composition nor plant performance is firmly predictable. It must be remembered that each of the values assumed in this or any other example is merely one value from a possible range.
>
> To start the computational procedure, numerous estimates about plant performance must be made. Application of the

mass-balance approach may show that two or more assumptions, although each is typical of plant operation, may not be mutually compatible, much as a problem in structural analysis may be "overdetermined."

In the short exercise provided, several spaces have been left blank. An empty box on a QFD signifies that: (1) the parameter represented has been given due consideration, and (2) it has proved to be unimportant for the problem worked.

To denote a required process capacity with a bold-line box, though hardly a necessary procedure in this simple example, will be useful in more complex examples where values of 10 or more required capacities are sought.

The QFD presented here as a method to assist computations of process capacity is closely related to the computation scheme proposed by Smith *(1)*.

EXAMPLE OF TREATMENT SYSTEMS

Material balances of systems involving sludge and liquid sidestreams will be further illustrated by four examples which, to a large degree, represent systems presently (1973) being used in full-scale plant designs (Figs. A-2 through A-5). The hypothetical effluent quality parameters, although arbitrarily chosen, do represent some currently specified requirements such as removal of large proportions of phosphorus and ammonia. Removal of COD is considered in Example 4.

All examples utilize primary clarification and a two-stage activated sludge process. The first stage is a high-rate activated sludge unit (HRAS), with provision for alum to be added to remove phosphorus. Sludge from the HRAS is removed in an intermediate clarifier. The second stage is a nitrifying activated sludge unit (NAS) for oxidizing ammonia to nitrate. Solids from NAS are removed in a final clarifier. Sludge from all three clarifiers is gravity thickened and ultimately dewatered by a vacuum filter and hauled to landfill. The filtrate is returned to the HRAS unit.

The first three examples differ only in the handling of sludge between the thickener and the vacuum filter. In the first example, the thickened sludge is stored for periods of up to 1 day to permit intermittent operation of the vacuum filter. Ferric chloride and lime are added as conditioners before filtration. In the second example, the thickened sludge is anaerobically digested for 30 days, conditioned with ferric chloride and lime, and vacuum filtered. Digester supernatant is returned to the HRAS unit. In the third example, the thickened sludge is heat conditioned, then dewatered on a vacuum filter without the addition of chemical conditioners. Included in the heat conditioning system is backup chemical feed system (lime and ferric chloride) so sludge can be conditioned and stabilized at pH above 11 for landfill disposal when the heat conditioner unit is down for repairs or maintenance. Decantate from the heat conditioner liquid-solids separation unit is returned to the HRAS unit. All vacuum filter systems have more than one unit so the plant can operate if one unit is down for repairs.

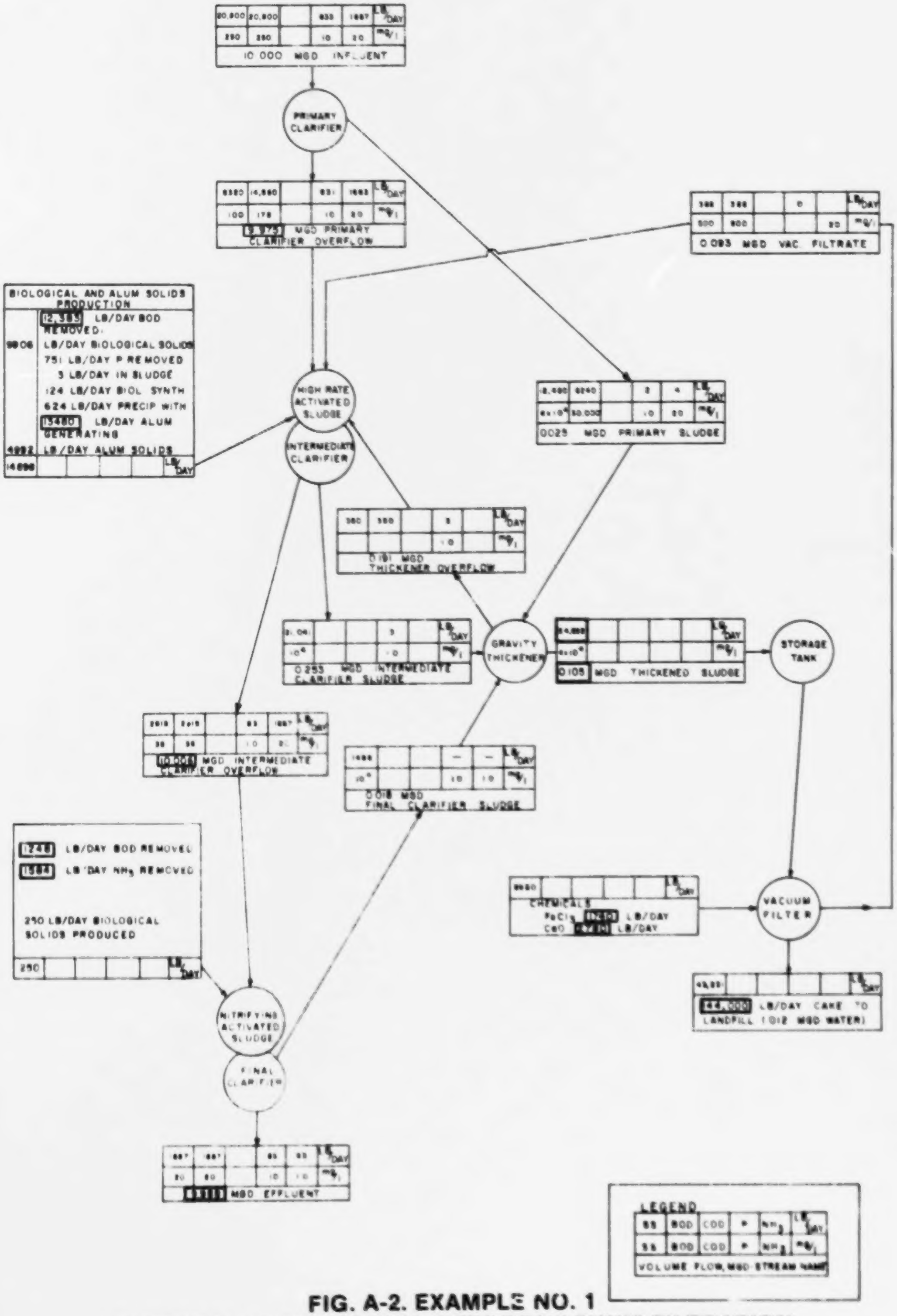
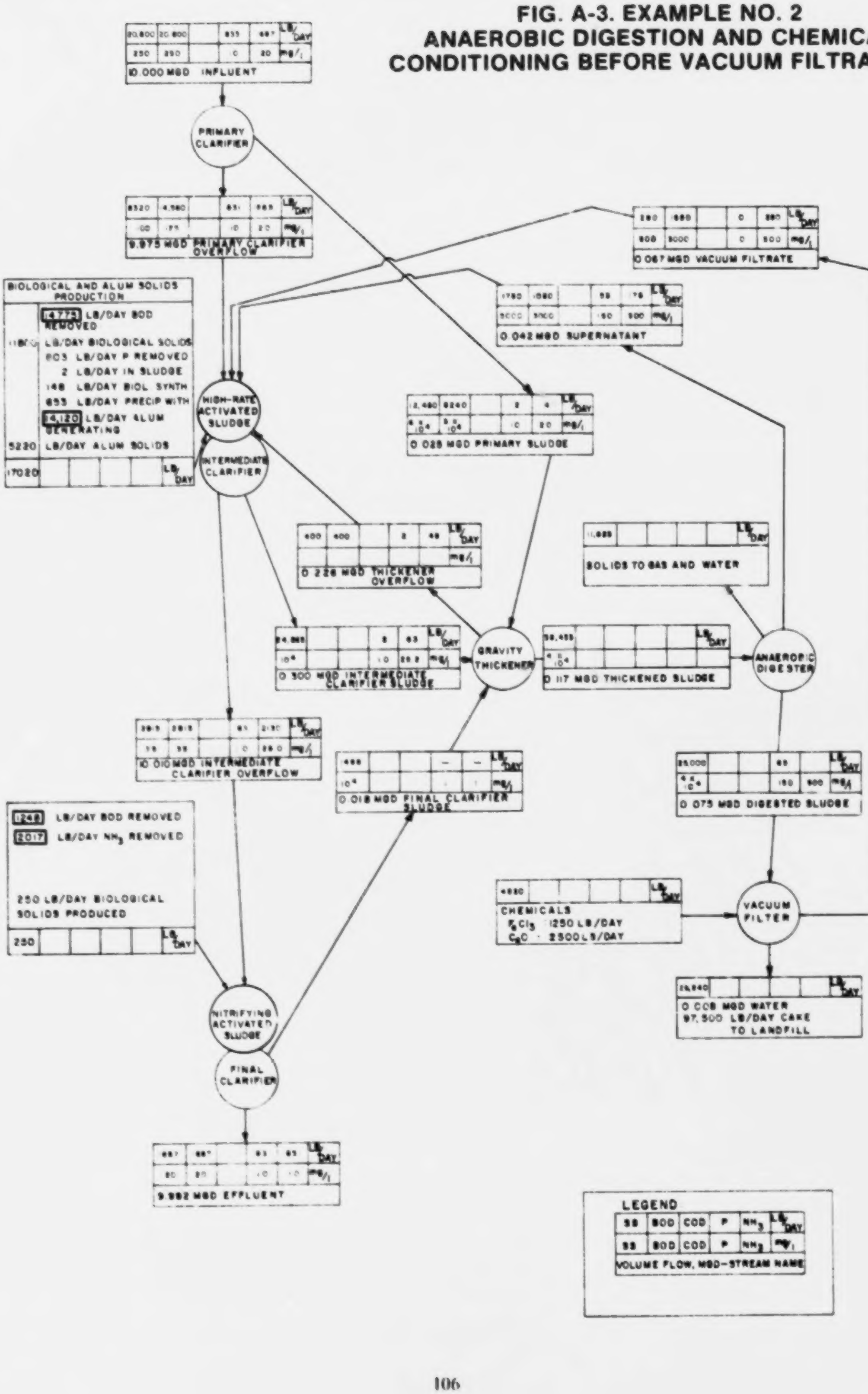

10.000 MGD INFLUENT
PRIMARY CLARIFIER
MGD PRIMARY CLARIFIER OVERFLOW
0.093 MGD VAC. FILTRATE
BIOLOGICAL AND ALUM SOLIDS PRODUCTION
12,385 LB/DAY BOD REMOVED:
9906 LB/DAY BIOLOGICAL SOLIDS
751 LB/DAY P REMOVED
3 LB/DAY IN SLUDGE
124 LB/DAY BIOL. SYNTH
624 LB/DAY PRECIP WITH
13480 LB/DAY ALUM GENERATING
4992 LB/DAY ALUM SOLIDS
14898
HIGH RATE ACTIVATED SLUDGE
INTERMEDIATE CLARIFIER
0.025 MGD PRIMARY SLUDGE
0.191 MGD THICKENER OVERFLOW
0.253 MGD INTERMEDIATE CLARIFIER SLUDGE
GRAVITY THICKENER
0.105 MGD THICKENED SLUDGE
STORAGE TANK
MGD INTERMEDIATE CLARIFIER OVERFLOW
0.018 MGD FINAL CLARIFIER SLUDGE
1248 LB/DAY BOD REMOVED
1584 LB/DAY NH3 REMOVED
250 LB/DAY BIOLOGICAL SOLIDS PRODUCED
250
CHEMICALS
FeCl3 LB/DAY
CaO LB/DAY
VACUUM FILTER
LB/DAY CAKE TO LANDFILL (.012 MGD WATER)
NITRIFYING ACTIVATED SLUDGE
FINAL CLARIFIER
MGD EFFLUENT
LEGEND
SS BOD COD P NH3 LB/DAY
SS BOD COD P NH3 mg/l
VOLUME FLOW, MGD STREAM NAME

FIG. A-2. EXAMPLE NO. 1
CHEMICAL CONDITIONING BEFORE VACUUM FILTRATION

**FIG. A-3. EXAMPLE NO. 2
ANAEROBIC DIGESTION AND CHEMICAL
CONDITIONING BEFORE VACUUM FILTRATION**



20,800 20,800 835 687 LB/DAY
250 250 10 20 mg/l
10.000 MGD INFLUENT
PRIMARY CLARIFIER
8320 4,980 831 663 LB/DAY
100 175 10 20 mg/l
9.975 MGD PRIMARY CLARIFIER OVERFLOW
BIOLOGICAL AND ALUM SOLIDS PRODUCTION
14775 LB/DAY BOD REMOVED
11800 LB/DAY BIOLOGICAL SOLIDS
803 LB/DAY P REMOVED
2 LB/DAY IN SLUDGE
148 LB/DAY BIOL SYNTH
653 LB/DAY PRECIP WITH
14,120 LB/DAY ALUM GENERATING
5220 LB/DAY ALUM SOLIDS
17020 LB/DAY
HIGH-RATE ACTIVATED SLUDGE
INTERMEDIATE CLARIFIER
280 1880 0 280 LB/DAY
500 3000 0 500 mg/l
0.067 MGD VACUUM FILTRATE
1750 1080 55 175 LB/DAY
5000 3000 150 500 mg/l
0.042 MGD SUPERNATANT
12,480 8240 2 4 LB/DAY
6 x 10⁴ 5 x 10⁴ 10 20 mg/l
0.025 MGD PRIMARY SLUDGE
400 400 2 49 LB/DAY
mg/l
0.226 MGD THICKENER OVERFLOW
11,025 LB/DAY
SOLIDS TO GAS AND WATER
24,860 2 63 LB/DAY
10⁴ 10 25.2 mg/l
0.300 MGD INTERMEDIATE CLARIFIER SLUDGE
GRAVITY THICKENER
58,455 LB/DAY
6 x 10⁴
0.117 MGD THICKENED SLUDGE
ANAEROBIC DIGESTER
2915 2915 83 2130 LB/DAY
35 35 0 28.0 mg/l
10.010 MGD INTERMEDIATE CLARIFIER OVERFLOW
466 — — LB/DAY
10⁴ 1 1 mg/l
0.018 MGD FINAL CLARIFIER SLUDGE
25,000 65 LB/DAY
4 x 10⁴ 150 500 mg/l
0.075 MGD DIGESTED SLUDGE
1248 LB/DAY BOD REMOVED
2017 LB/DAY NH₃ REMOVED
250 LB/DAY BIOLOGICAL SOLIDS PRODUCED
250 LB/DAY
4830 LB/DAY
CHEMICALS
FeCl₃ 1250 LB/DAY
CaO 2500 LB/DAY
VACUUM FILTER
26,840 LB/DAY
0.008 MGD WATER
97,500 LB/DAY CAKE TO LANDFILL
NITRIFYING ACTIVATED SLUDGE
FINAL CLARIFIER
667 667 83 83 LB/DAY
80 80 10 10 mg/l
9.982 MGD EFFLUENT
LEGEND
SS BOD COD P NH₃ LB/DAY
SS BOD COD P NH₃ mg/l
VOLUME FLOW, MGD-STREAM NAME

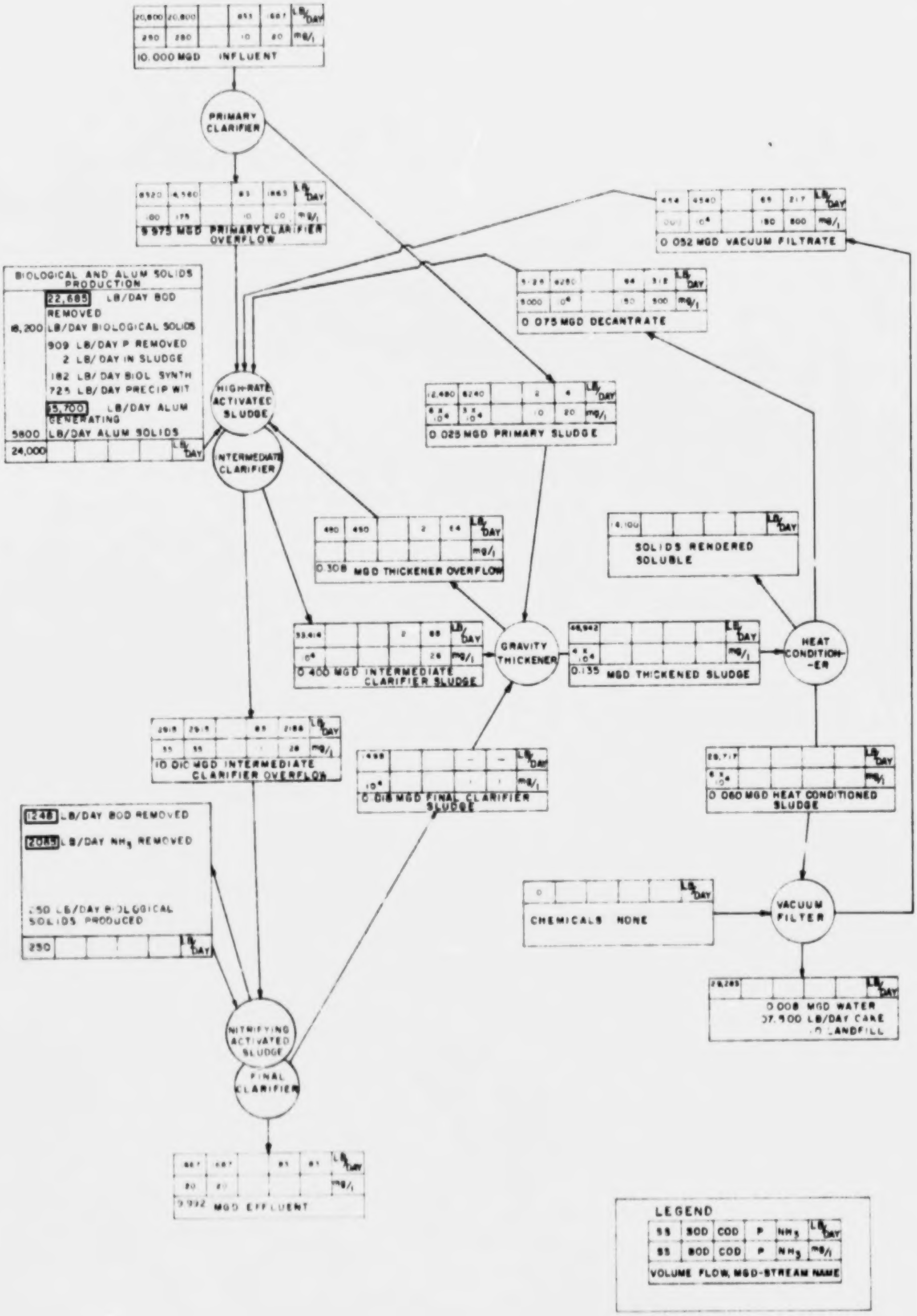

20,800 20,800 651 1667 LB/DAY
250 250 10 20 mg/l
10.000 MGD INFLUENT
PRIMARY CLARIFIER
8520 14,560 83 1663 LB/DAY
100 175 10 20 mg/l
9.975 MGD PRIMARY CLARIFIER OVERFLOW
BIOLOGICAL AND ALUM SOLIDS PRODUCTION
22,685 LB/DAY BOD REMOVED
18,200 LB/DAY BIOLOGICAL SOLIDS
909 LB/DAY P REMOVED
2 LB/DAY IN SLUDGE
182 LB/DAY BIOL SYNTH
725 LB/DAY PRECIP WIT
15,700 LB/DAY ALUM GENERATING
5800 LB/DAY ALUM SOLIDS
24,000 LB/DAY
HIGH-RATE ACTIVATED SLUDGE
INTERMEDIATE CLARIFIER
434 4540 65 217 LB/DAY
1000 10⁴ 150 500 mg/l
0 052 MGD VACUUM FILTRATE
5126 6250 94 312 LB/DAY
5000 10⁴ 150 500 mg/l
0 075 MGD DECANTRATE
12,480 6240 2 4 LB/DAY
6 x 10⁴ 3 x 10⁴ 10 20 mg/l
0 025 MGD PRIMARY SLUDGE
490 490 2 64 LB/DAY
mg/l
0.308 MGD THICKENER OVERFLOW
14,100 LB/DAY
SOLIDS RENDERED SOLUBLE
33,414 2 88 LB/DAY
10⁴ 26 mg/l
0 400 MGD INTERMEDIATE CLARIFIER SLUDGE
GRAVITY THICKENER
46,942 LB/DAY
4 x 10⁴ mg/l
0.135 MGD THICKENED SLUDGE
HEAT CONDITION-ER
2915 2915 85 2188 LB/DAY
35 35 1 26 mg/l
10 010 MGD INTERMEDIATE CLARIFIER OVERFLOW
1499 — — LB/DAY
10⁴ 1 1 mg/l
0 018 MGD FINAL CLARIFIER SLUDGE
29,717 LB/DAY
6 x 10⁴ mg/l
0 060 MGD HEAT CONDITIONED SLUDGE
1248 LB/DAY BOD REMOVED
2083 LB/DAY NH₃ REMOVED
250 LB/DAY BIOLOGICAL SOLIDS PRODUCED
250 LB/DAY
0 LB/DAY
CHEMICALS NONE
VACUUM FILTER
29,283 LB/DAY
0.008 MGD WATER
37,500 LB/DAY CAKE
TO LANDFILL
NITRIFYING ACTIVATED SLUDGE
FINAL CLARIFIER
667 667 83 83 LB/DAY
20 20 mg/l
9.992 MGD EFFLUENT
LEGEND
SS BOD COD P NH₃ LB/DAY
SS BOD COD P NH₃ mg/l
VOLUME FLOW, MGD-STREAM NAME

FIG. A-4. EXAMPLE NO. 3
HEAT CONDITIONING BEFORE VACUUM FILTRATION

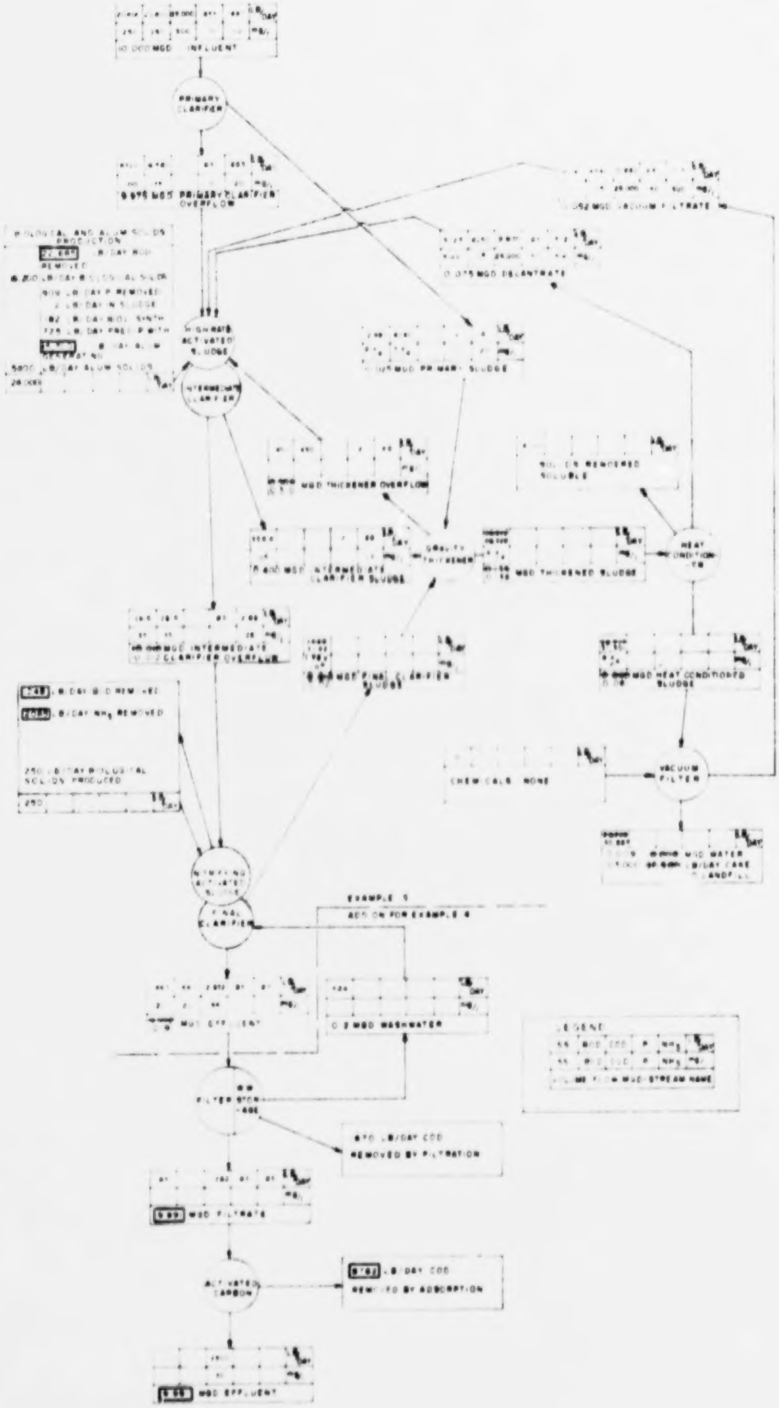

10.000 MGD INFLUENT
PRIMARY CLARIFIER
MGD PRIMARY CLARIFIER OVERFLOW
BIOLOGICAL AND ALUM SOLIDS PRODUCTION
HIGH RATE ACTIVATED SLUDGE
INTERMEDIATE CLARIFIER
MGD VACUUM FILTRATE
MGD DECANTRATE
MGD PRIMARY SLUDGE
MGD THICKENER OVERFLOW
SOLIDS RENDERED SOLUBLE
MGD INTERMEDIATE CLARIFIER SLUDGE
GRAVITY THICKENER
MGD THICKENED SLUDGE
HEAT CONDITIONER
MGD INTERMEDIATE CLARIFIER OVERFLOW
MGD FINAL CLARIFIER SLUDGE
MGD HEAT CONDITIONED SLUDGE
LB/DAY BOD REMOVED
LB/DAY NH3 REMOVED
250 LB/DAY BIOLOGICAL SOLIDS PRODUCED
CHEMICALS: NONE
VACUUM FILTER
MGD WATER
LB/DAY CAKE
LANDFILL
NITRIFYING ACTIVATED SLUDGE
FINAL CLARIFIER
EXAMPLE 5
ADD ON FOR EXAMPLE 4
MGD EFFLUENT
0.2 MGD WASHWATER
LEGEND
FILTER STORAGE
870 LB/DAY COD
REMOVED BY FILTRATION
MGD FILTRATE
ACTIVATED CARBON
LB/DAY COD
REMOVED BY ADSORPTION
MGD EFFLUENT

FIG. A-5. EXAMPLE NO. 4
HEAT CONDITIONING BEFORE VACUUM FILTRATION.
COAL/SAND AND ACTIVATED CARBON FILTRATION OF EFFLUENT.

The first three examples are of plants that provide good removal of suspended solids, BOD, phosphorus, and ammonia; the fourth example is of a plant designed to provide a high degree of COD removal as well. The effluent from a plant identical to that of Example 3 (with heat conditioning of the sludge) is put through a dual-media filter for suspended solids removal, then through an activated carbon adsorption unit. Wash water from the filter is returned to the final clarifier.

For all the examples, the 24-hour average influent conditions are: 10 mgd of flow, 250 mg/l of 5-day BOD, 250 mg/l of suspended solids, 10 mg/l of soluble phosphorus (P), and 20 mg/l of ammonia (NH_3). It is required that effluent concentrations not exceed: 20 mg/l BOD, 20 mg/l suspended solids, 1.0 mg/l P, and 1.0 mg/l NH_3. For Example 4, it is required that effluent COD not exceed 30 mg/l. Steady state conditions are assumed. These influent and effluent values are summarized in Table A-1.

Also shown in Table A-1 are the given performance characteristics assumed for each process, such as detention time, overflow rate, percentage removal of suspended solids, and so on. The capacity parameters that have to be evaluated to determine process costs are listed in the second column of Table A-2. Quantitative flow diagrams for the four examples are presented in Figs. A-2 through A-5.

The computation procedure using the QFD's is that described previously with two additional assumptions: (1) one may assume that the concentrations of entirely soluble components, P and NH_3, are not changed by gravity settling equipment; i.e., the concentrations in underflow and overflow from a clarifier or sludge thickener are the same, and (2) the mass per day of a constituent "removed" from a process is equal to the mass per day of that constituent flowing into the process minus the mass per day flowing out of the process in the principal stream, usually a clarifier overflow. The mass is "removed" generally by withdrawal in a sludge stream or liquid sidestream and by chemical or biological conversion to other matter, as in oxidation or digestion.

The QFD's are intended to help estimate the required capacities of the component processes, taking into account the layout and performance of the plant as a whole. Values of the capacity parameters are transferred from the bold-line boxes of the completed QFD's to Table A-2.

COST EFFECTIVENESS ANALYSIS

EPA regulations (40 CFR Part 35) require that a cost effectiveness analysis be made for alternative waste-treatment management techniques before a construction grant is awarded. Systems for sludge processing and liquid sidestream treatment are subject to a cost effectiveness analysis. The quantitative flow diagram can be a very useful tool in such an analysis, because it provides a method of determining the impact of a particular sludge treatment alternative on total treatment system costs.

DISCUSSION AND CONCLUSIONS

Recycle from a process may significantly affect the loading on that process. In Figs. A-2, A-3, and A-4, for the three examples that differed only in method of sludge handling after thickening and before dewatering, notice the wide range in hydraulic flow and mass suspended

TABLE A-1. ASSUMPTIONS OF LOADING AND PERFORMANCE

Process	Volume (Hydraulics)	Suspended Solids	BOD	COD (Considered in Example 4 Only)	Phosphorus	Ammonia
Influent	10 mgd (24-hr average)	250 mg/l	250 mg/l	300 mg/l, all but 20% of which can be removed by oxidation and sedimentation	10 mg/l	20 mg/l
Effluent		20 mg/l	20 mg/l	30 mg/l	1.0 mg/l	1.0 mg/l
Primary clarifier	10 mgd	60% removal to thickener; sludge concentration = 6% solids	30% removal to thickener		Concentrations in overflow and sludge stream are equal	Concentrations in overflow and sludge stream are equal
High rate activated sludge basin	Volume of sludge returned from intermediate clarifier = 50% of influent	MLSS = 2,500 mg/l; 0.8 lb SS produced/lb BOD removed	0.75 lb/day BOD removed per lb MLSS; 0.8 lb O_2 required per lb BOD removed		1.0 lb P removed by biological synthesis per 100 lb BOD removed; other P: 21.6 lb alum/lb P, 8 lb sludge/lb P	
Intermediate clarifier	Overflow rate: 700 gpd/sq ft	Overflow: 35 mg/l; sludge: 1% solids	Overflow: 35 mg/l		Concentrations in overflow and sludge stream are equal (1.0 mg/l)	Concentrations in overflow and sludge stream are equal
Nitrifying activated sludge basin	Volume of sludge returned from final clarifier = 50% of influent; retention time = 10 hr, based on influent	MLSS = 1,500 mg/l; 0.2 lb SS produced BOD removed				
Final clarifier	Overflow rate: 600 gpd/sq ft	Waste activated sludge: 1% solids; example No. 4: washwater sludge: 6% solids			Concentrations in overflow and sludge stream are equal	Concentrations in overflow and sludge stream are equal
Dual-media filter (example No. 4 only)	5 gpm/sq ft; wash water = 2% of filtrate; recycled to final clarifier	95% SS removal		20 mg/l removed		

TABLE A-1. ASSUMPTIONS OF LOADING AND PERFORMANCE (Continued)

Process	Volume, Hydraulics	Suspended Solids	BOD	COD (Considered in Example 4 Only)	Phosphorus	Ammonia
Activated carbon upflow col. (example No. 4 only)						
Gravity thickener		Sludge: 4% solids. 99% solids capture	Overflow: BOD concentration approximately equal to SS concentration		Concentrations in overflow and outflowing sludge stream are equal	Concentrations in overflow and outflowing sludge stream are equal
Storage tank (example No. 1 only)						
Anaerobic digester (example 2 only)	Detention time = 30 days	Sludge out: 4% solids; 30% of SS volatilized				
Supernatant		5,000 mg/l	3,000 mg/l	10,000 mg/l (10% nonbiodegradable)	150 mg/l	500 mg/l
Heat conditioner decantate (examples Nos. 3 and 4 only)	0.075 mgd to HRAS* basin	30% of SS to heat conditioner rendered soluble. 5,000 mg/l sludge at 6% solids	10,000 mg/l	25,000 mg/l (30% nonbiodegradable)	150 mg/l	500 mg/l
$FeCl_3$ and lime (CaO)	Per 100 lb sludge SS: add 5 lb $FeCl_3$ (examples Nos. 1, 2) 8 lb CaO (example No. 1) 10 lb CaO (example No. 2)	Example No. 1: SS = 25.8% of incoming sludge SS; Example No. 2: SS = 18.1% of incoming sludge SS; Examples Nos. 3, 4: none				
Vacuum filter		Cake: 30% solids				
Filtrate	To HRAS basin	Examples Nos. 1, 2: 500 mg/l Examples Nos. 3, 4: 1,000 mg/l	Example No. 1: 500 mg/l; Example No. 2: 3,000 mg/l; Examples Nos. 3, 4: 10,000 mg/l	25,000 mg/l	Examples Nos. 1, 2: None; Examples Nos. 3, 4: 150 mg/l	Examples No. 1 not specified Examples Nos. 2, 3, 4: 500 mg/l
Landfill (5 miles away)						

*High rate activated sludge

TABLE A-2. CAPACITIES AND COSTS

Process	Capacity Parameter(s)	Example No.	Capacity Parameter Values	
Primary clarifier	Overflow, mgd	1	10.0	
		2	10.0	
		3	10.0	
		4	10.0	
High rate activated sludge (HRAS)	Pounds/day BOD removed	1	12,383	
		2	14,775	
		3	21,685	
		4	21,685	
Aeration equipment for HRAS basin	Pounds/day BOD removed	1	12,383	
		2	14,775	
		3	21,685	
		4	21,685	
Alum	Pounds/day added	1	13,480	
		2	14,120	
		3	15,700	
		4	15,700	
Intermediate clarifier and sludge return pumps	Overflow, mgd	1	10.0	
		2	10.0	
		3	10.0	
		4	10.0	
Nitrifying activated sludge basin (NAS)	Inflow, mgd	1	10.0	
		2	10.0	
		3	10.0	
		4	10.0	
			BOD	NH_3
Aeration equipment for NAS basin	Pounds/day BOD removed Pounds-day NH_3 removed	1	1,248	1,584
		2	1,248	2,017
		3	1,248	2,085
		4	1,248	2,085

TABLE A-2. CAPACITIES AND COSTS (Continued)

Process	Capacity Parameter(s)	Example No.	Capacity Parameter Values	
Final clarifier and sludge return pumps	Overflow, mgd,	1	10.0	
		2	10.0	
		3	10.0	
		4	10.2	
Dual-media filter	Inflow, mgd	4	10.2	
Activated carbon upflow column	Inflow (10 mgd), COD removed, pounds/day	4	8,762	
Gravity thickener	Pounds/day SS in	1	35,019	
		2	38,833	
		3	47,392	
		4	48,976	
Sludge handling before dewatering:				
Aerated storage	Inflow, mgd	1	0.105	
Anaerobic digestion	Inflow, mgd	2	0.117	
Heat conditioning	Pounds/day SS in inflow	3	46,942	
Heat conditioning	Pounds/day SS in inflow	4	48,526	
			$FeCl_3$	CaO
			Pounds/day	
$FeCl_3$ and lime (CaO)		1	1,740	2,780
		2	1,250	2,500
		3	0	0
		4	0	0
			Flow	SS
Vacuum filter	Inflow (mgd):	1	0.105	34,669
		2	0.075	25,000
		3	0.060	29,717
		4	0.061	31,301
Landfill	Pounds/day cake	1	144,000	
		2	97,500	
		3	97,500	
		4	103,000	

solids flow *into* the storage tank, anaerobic digester, or heat conditioner. One expects to find differences in outflow from different processes, but one all too often neglects the possible differences in *inflow* that result directly or indirectly from the sidestreams recycled from these processes. The differences in suspended solids loadings result both from recycled suspended solids and from recycled BOD and P, whose removal in the activated sludge basin generates additional suspended solids.

Recycle from a process may significantly affect the loading on other processes. In the examples considered, the primary clarifier receives no recycled sidestreams, and thus its capacity and cost are the same for all examples. The volume of recycled sidestreams is usually only about 1 to 3 percent of the plant inflow, so processes whose capacity parameter (for costing purposes) is volumetric flow rate, such as the intermediate and final clarifiers and the NAS basin in these examples, are not significantly affected.

However, the mass flow rate of some recycled pollutants may not be negligible. In Example 2, consider the 3,130 lb/day of BOD recycled to the HRAS basin, which is equal to more than 20 percent of the BOD entering the basin via the untreated wastewater stream from the primary clarifier. In Example 3 consider the 4,000 lb/day of suspended solids and the 11,040 lb/day of BOD recycled to the HRAS basin. These loads are equal to 48 and 75 percent, respectively, of the suspended solids and BOD loads entering from the primary clarifier. As shown in Table A-2, the required capacities of the HRAS basin and its aeration equipment, the alum dosage, and size of the gravity thickener are all affected by the choice of sludge handling process.

Processes added to upgrade the plant can affect other process loadings. In Example 4, where the effluent from a plant identical to that of Example 3 is filtered and passed through a carbon column for COD removal, there is an additional sidestream: filter washwater containing 1,584 lb/day suspended solids, recycled to the final clarifier. The volumetric and mass loadings of this sidestream appear to be insignificant, yet it is still advisable to consider their effect through the QFD just to make sure. Indeed, the addition of washwater solids leads to differences in capacity required for the gravity thickener, the heat conditioner, the vacuum filter, and the landfill operation of only a little more than 5 percent, not significant considering the low order of accuracy in the cost estimation considered. However, note that the mass load of suspended solids from the final clarifier to the thickener has more than doubled. There is only a slight increase in volumetric flow because the washwater solids may be assumed to settle easily to about 5 or 6 percent concentration, in contrast to the relatively thin waste activated sludge. The QFD therefore helps assure one as to which factors are insignificant, as well as to alert one as to which factors are important.

Without a complete diagram and its analysis, it is not possible to select the required capacity of process equipment when recycling of pollutants being removed is involved. This is probably one of the most important design outputs that an analysis such as that described herein will provide which cannot properly be obtained by any "estimating" or application of arbitrary "safety factors." A simple example will illustrate this. In determining the solids handling capacity of, for example, the heat conditioning equipment in Process No. 3, one could estimate it thus: the total solids generated in treating the 10 mgd of wastewater flow averages about 34,700 lb/day, as shown in Process No. 1. The recycled solids in the decant liquor and infiltrate are estimated to be about 3,600 lb/day. Therefore, the capacity of the heat conditioning equipment should be the sum or about 38,300 lb/day. Actually, it can be noted from the analysis that the total solids to be handled will be about 47,000 lb/day — an "estimating" error of 23 percent. The crude and incomplete analysis failed to take into account the solids produced by the other pollutants, such as BOD, ammonia, and phosphorus in the recycled stream. A complete flow diagram, with all solid and liquid streams identified, precludes serious errors in plant and process equipment sizing.

It should be emphasized that the examples shown with various assumed performance and operational parameters for the different unit processes utilize only one set of values. Because these parameters may have a wide range of values, any QFD should be examined for variations of the performance parameters. The influence of a specific value that characterizes a unit process performance can be readily determined once a QFD has been drawn up.

REFERENCE

1. Smith, Robert, "Preliminary Design of Wastewater Systems," *Journal of the Sanitary Division, ASCE, 95,* No. SA1, p 117 (February 1969).

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